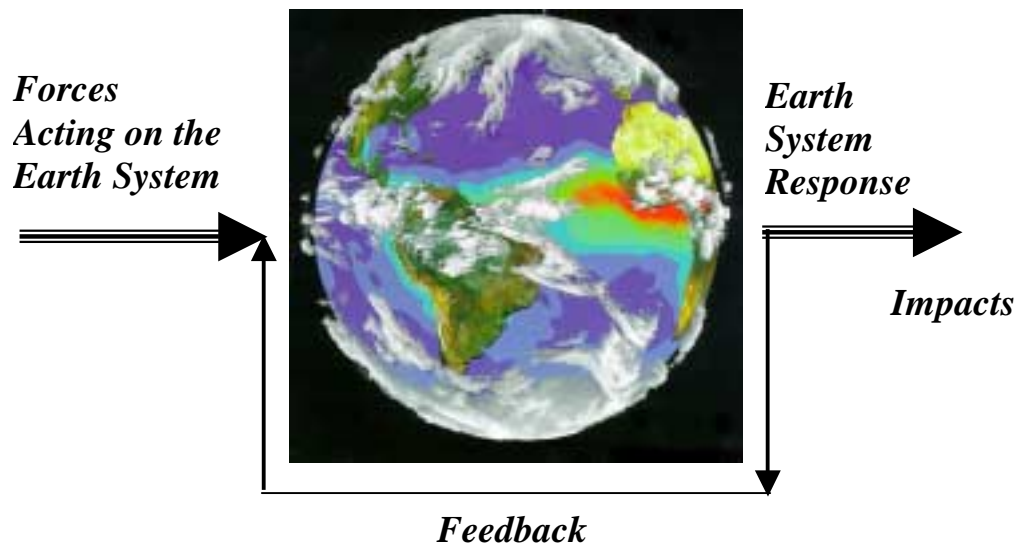


UNDERSTANDING EARTH SYSTEM CHANGE

NASA's Earth Science Enterprise

Research Strategy

for
2000-2010



December 2000

Preface

This Research Strategy has been prepared by NASA's Office of Earth Science in consultation with its Earth System Science and Applications Advisory Committee (ESSAAC) and selected members of the broader Earth science community. This edition incorporates comments from a formal review by the National Academy of Sciences.

The Research Strategy is one of a family of strategy documents being published to guide the Earth Science Enterprise for the new decade. Others are the Earth Science Enterprise Strategic Plan, Technology Strategy, and Applications Strategy. Underpinning this Research Strategy is a set of chapters (published separately) describing the planned activities under the principal research themes. The Research Strategy and these chapters constitute the Enterprise's Science Implementation Plan. The full set of Earth Science Enterprise planning documents can be obtained by visit the homepage at www.earth.nasa.gov.

NASA EARTH SCIENCE ENTERPRISE RESEARCH STRATEGY FOR 2000-2010

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EARTH SCIENCE ENTERPRISE RESEARCH STRATEGY FOR 2000-2010

EXECUTIVE SUMMARY

The mission of NASA's Earth Science Enterprise (ESE) is to develop a scientific understanding of the Earth system and its response to natural or human-induced changes to enable improved prediction capability for climate, weather, and natural hazards. The Earth Science Enterprise has three basic activities: a **research** program to increase in our knowledge of the Earth system, an **applications** program to demonstrate practical use of Earth system information to decision-makers in governments, businesses, and elsewhere, and a **technology** program to enable new or lower cost capabilities for the study of the Earth system in the future. NASA's unique capabilities in satellite and suborbital observing systems, information systems, and global models combine to provide the continuing advances in these three areas. This plan, the "NASA Earth Science Enterprise Research Strategy for 2000-2010" describes the strategy that ESE is taking through the new decade for the conduct of its research programs. Separate documents describe the plans for ESE's applications and technology programs, although each will reflect the crucial links between these areas.

The NASA Earth Science program is driven by the recognition of the societal importance of the natural variability of the planetary environment and the realization that humans are no longer passive participants in the evolution of the Earth system, but are instead causing significant changes in atmospheric composition, land use and land cover, water resources, and biodiversity. NASA embraces the concept of "Earth system science" – the idea that the Earth can only be understood as an interactive system that includes the atmosphere, oceans, continents and life. This concept of Earth system science goes far beyond the traditional Earth science disciplines to include a strong focus on interdisciplinary science to understand the interactions between the Earth system components. NASA also clearly recognizes the societal importance of Earth system science, as the scope and pace of natural and human induced changes occurring in the Earth system combine with increasing pressures on land, water, and air resources to increase the demands for accurate environmental information about the present and future.

Earth system science is a highly international and diverse discipline that cannot be studied by a single agency alone. NASA's Earth Science Enterprise is a part of a larger national effort, the multi-agency United States Global Change Research Program (USGCRP) as well as integrated with international scientific activities such as the World Climate Research Program and the International Geosphere-Biosphere Programme. NASA's contributions are the unique vantage point of space, the use of high performance aircraft, innovative remote sensing and in situ measurement techniques, and the development of large-scale data systems and computationally demanding global models designed to assimilate global environmental data and simulate Earth system behavior. NASA's strategy is designed to complement that of other national and international partners, but recognizes that the ESE goals, like those of its counterparts, are to provide answers to scientific questions and deliver objective scientific information to environmental decision-makers. As such, NASA has an "end-to-end" strategy to assure that all the information, understanding, and capabilities derived from its research programs achieve maximum usefulness to the scientific and decision-making communities. Also, it is important to note that the ESE has a single research program, in which space observations, ground-based and atmospheric in situ observations, laboratory process studies, and computational modeling and data analysis all work together to provide the needed answers and information.

The Earth Science Enterprise has defined its Research Strategy around a hierarchy of scientific questions. At the highest level, the Enterprise is attempting to provide an answer to the one overarching question **"How is the Earth changing and what are the consequences for life on Earth?"** The magnitude and

scope of this question are too large to allow a simple answer. The next tier of questions provides a structure constituting the conceptual approach ESE is taking to improve our knowledge of the Earth system.

- *How is the global Earth system changing?*
- *What are the primary forcings of the Earth system?*
- *How does the Earth system respond to natural and human-induced changes?*
- *What are the consequences of change in the Earth system for human civilization?*
- *How well can we predict future changes in the Earth system?*

These five questions define a pathway of “variability, forcing, response, consequence, and prediction” that is taken to further enumerate more specific questions (in Table 1) which provide direction and focus to the program. This structure highlights one of the most important and intellectual challenges of the study of the Earth system – that most responses the Earth system makes to a forcing (either natural or human-induced) can in turn become a forcing factors themselves. This is the definition of a feedback process. Thus, the understanding of feedback processes in the Earth system is central to NASA’s study of the Earth system. The third tier of questions refines and delimits the components of and processes within the Earth system of particular interest to ESE.

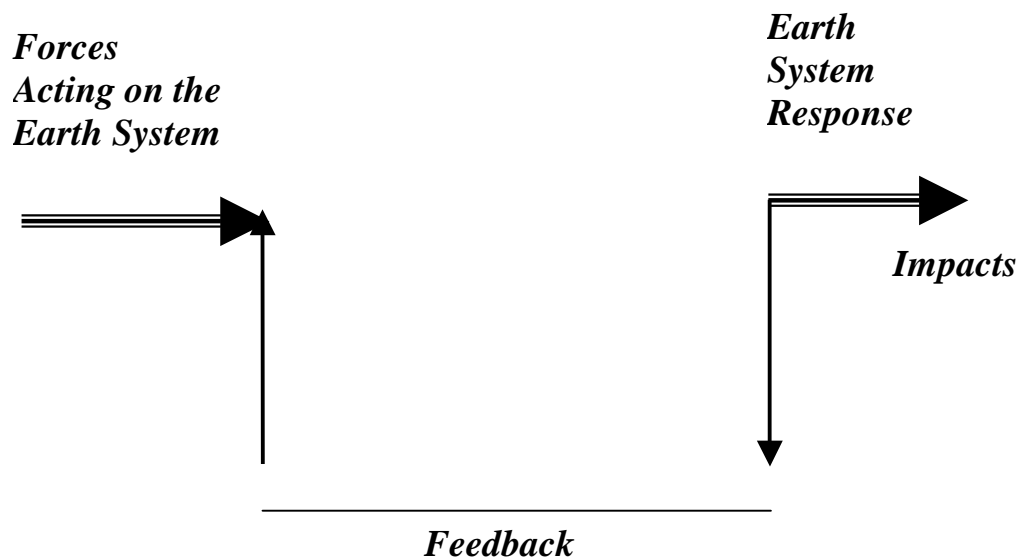


Figure 1: Earth System Conceptual Diagram

Hierarchy of Science Questions

Overall: *How is the Earth changing and what are the consequences for life on Earth?*

- ***How is the global Earth system changing?(Variability)***
 - How are global precipitation, evaporation, and the cycling of water changing?
 - How is the global ocean circulation varying on interannual, decadal, and longer time scales?
 - How are global ecosystems changing?
 - How is stratospheric ozone changing, as the abundance of ozone-destroying chemicals decreases and new substitutes increases?
 - What changes are occurring in the mass of the Earth's ice cover?
 - What are the motions of the Earth and the Earth's interior, and what information can be inferred about Earth's internal processes?
- ***What are the primary forcings of the Earth system? (Forcing)***
 - What trends in atmospheric constituents and solar radiation are driving global climate?
 - What changes are occurring in global land cover and land use, and what are their causes?
 - How is the Earth's surface being transformed and how can such information be used to predict future changes?
- ***How does the Earth system respond to natural and human-induced changes?(Response)***
 - What are the effects of clouds and surface hydrologic processes on Earth's climate?
 - How do ecosystems respond to and affect global environmental change and the carbon cycle?
 - How can climate variations induce changes in the global ocean circulation?
 - How do stratospheric trace constituents respond to change in climate and atmospheric composition?
 - How is global sea level affected by climate change?
 - What are the effects of regional pollution on the global atmosphere, and the effects of global chemical and climate changes on regional air quality?
- ***What are the consequences of change in the Earth system for human civilization?(Consequences)***
 - How are variations in local weather, precipitation and water resources related to global climate variation?
 - What are the consequences of land cover and land use change for the sustainability of ecosystems and economic productivity?
 - What are the consequences of climate and sea level changes and increased human activities on coastal regions?
- ***How well can we predict future changes in the Earth system? (Prediction)***
 - How can weather forecast duration and reliability be improved by new space-based observations, data assimilation, and modeling?
 - How well can transient climate variations be understood and predicted?
 - How well can long-term climatic trends be assessed or predicted?
 - How well can future atmospheric chemical impacts on ozone and climate be predicted?

- How well can cycling of carbon through the Earth system be modeled, and how reliable are predictions of future atmospheric concentrations of carbon dioxide and methane by these models?

The scientific breadth of Earth system research is enormous. A brief summary of the subjects considered in each of the five areas identified above follows:

- **Variability:** includes the internal variability of the coupled atmosphere-hydrosphere-biosphere system, with variability ranging from minutes to hours to days to all the way through seasonal, interannual, and longer timescales, as well as trends associated with human-induced changes, especially those occurring at decadal time scales (and longer). Emphasis is on global and large-scale regional variability.
- **Forcing:** includes naturally-occurring forcing factors such as solar irradiance, volcanic eruptions, and land surface evolution, as well as human-induced changes such as increased atmospheric composition of radiatively and chemically active gases and particulates, changes in land use and cover, and changes in availability and quality of water.
- **Response:** includes study of the processes that couple different components of the Earth system and give rise to feedback effects. Particular interest exists in the response of cloud distributions to changes in atmospheric circulation, the response of global ecosystems to changes in temperature, nutrients, and other factors, the atmospheric ozone response to precursors for both its production and destruction, and the response of polar ice to climate change.
- **Consequences:** includes study of local and regional impacts of changes that may be taking place on a global scale, as well as of the possible changes in the extremes of distributions of temperature and precipitation. Work on consequences is carried out through both the research and applications programs. ESE's Applications program pursues demonstration projects applying Earth science, data and technology to areas of resource management, disaster management, community growth, and environmental quality. The ESE Application Strategy (ESE, 2000b) describes this program
- **Prediction:** includes the improvements of environmental predictions, especially those that can accrue from innovative use of new data types provided by ESE. These address issues such as climate and weather on time scales from day-to-day, seasonal, interannual, and decadal, as well as composition of the atmosphere, including pollutants such as ozone and radiatively active gases such as carbon dioxide and methane.

Given the wide range of disciplines and processes that could be productively studied, a number of prioritization criteria are defined to help in selecting and ordering both the specific scientific questions and programs to be implemented. From a scientific perspective, the following criteria are considered to be in descending order of priority, starting with Scientific Return; from the standpoint of implementation, they are listed in ascending order of priority:

- **Scientific Return:** the significance of the expected increase in our fundamental knowledge of some Earth system component or process, especially concerning the reduction of uncertainty, resolution of competing theories, or clear identification of the direction and magnitude of a feedback effect
- **Benefit to Society:** the extent to which the research outcome may be productively utilized on some relevant time scale for greater societal benefit (governmental, economic, individual)
- **Mandated Programs:** some NASA programs, such as the study of stratospheric ozone and continuity of the Landsat program, are required by law. Other activities may be given particular importance in the Federal budget at some point in time.
- **Appropriate for NASA:** the extent to which an activity makes valuable use of the unique capabilities of NASA, and could not be done easily by other governmental or private entities. In many (but not all)

cases, questions addressed by NASA take place at large regional to global scales, involve seasonal and longer response periods, and deal with larger impacts than are questions addressed by other agencies.

- **Partnership Opportunity:** the extent to which needed work can be carried out in conjunction with partners, especially (but not exclusively) those of operational agencies in the US and abroad and partner space research agencies around the world.
- **Technology Readiness:** the extent to which current technology enables a question to be productively addressed (and activities implemented). Note that where interest exists and technology does not, investments by ESE's technology program can provide for the needed advances.
- **Program Balance:** to assure overall progress, it is important that resources be distributed in a way that ensures scientific progress is not impeded by the lack of key information about some particular Earth system component or process. This is especially true for improvements in understanding of consequences and capability for prediction, which could be severely limited by lack of understanding of variability, forcing factors, and response mechanisms.
- **Cost:** required resources must be available if a particular question is to be addressed or a mission is to be implemented.

The application of the prioritization criteria to the scientific questions presented allows for prioritization within each category (e.g., variability), but does not permit a linear priority ordering of all the questions. There is a logical progression associated with the research program, in that it is impossible to provide unambiguous answers to questions about consequence and prediction without a knowledge of the variability, forcing, and response processes that underlie them. However, it is not practical to defer all study of consequence and prediction until all uncertainties in the three other areas have been eliminated. The balance among the different areas may differ for different Earth system components or processes, and will evolve over time as the state of knowledge advances. NASA intends to periodically assess its progress on these priorities in consultation with the U.S. National Research Council.

The research program that will address the questions posed in this plan consists of several elements:

- **Basic Research and Data Analysis:** the conceptual source of Earth system science questions and strategies to address them. This part of the program provides the "feedback loop" and assures the results of scientific studies are helping to focus the scientific questions being addressed. It also includes the development of models that are used to integrate piecemeal findings, assimilate observed data and provide the predictive capability needed by ESE.
- **Systematic Measurements:** the long-term (typically but not necessarily continuous) measurement of a select number of critical environmental parameters, typically those that cannot currently be inferred from other parameters. For these measurements, the focus will be on the construction of consistent data sets from multi-instrument, multi-platform, and typically multi-year observations with careful attention to calibration and validation. These typically will involve incremental advances in technology rather than revolutionary innovations. By the end of this decade, an increasing fraction of these may be obtained from operational entities, as the quality, calibration, and availability of such systems are improved to meet scientific research needs.
- **Exploratory Measurements:** those observations that can yield new scientific breakthroughs by providing comprehensive information about a particular Earth system component or process. These are intended to be pursued for a finite period of time. They are likely to take advantage of innovative, even revolutionary, technologies.
- **Operational Precursor & Technology Demonstration Missions:** projects that aim to demonstrate new instrument and related technologies to either enable a transition to an operational environmental monitoring system, or to achieve a new capability for research. In the former case, such missions will be

undertaken where the operational partner agency has a commitment and a plan to use them. Some operational precursor and technology demonstration missions are focused on reducing the cost of making measurements of established importance, while others focus on making measurements not possible or practical previously.

- **Data Management and Distribution:** the vast amounts of data that can be generated by ESE must be archived and distributed in a way to support their easy use by the science and applications communities. Data systems that can facilitate use of data and information, especially those of different types as needed for interdisciplinary science studies, are required.

- **Assessment:** it is important to “complete the cycle” of scientific research and assure that the large body of information obtained by the Enterprise goes through a synthesis process generates new or expanded knowledge of the Earth system. Organized national and international assessments are one essential means of ensuring that appropriate integration of separate findings is actually completed. Assessments support both the basic research and the applications communities, contributing to such major activities as the Intergovernmental Panel on Climate Change deliberations, World Meteorological Organization findings on ozone, and conclusions of the US National Assessment of climate change impacts. While assessments are important scientifically, they can also be starting components of a broader applications program.

Although the ESE research strategy is laid out in terms of variability, forcing, response, consequence, and prediction, much of its actual implementation will of necessity be carried out in a construct reflective of the components of the Earth system. The approach used most recently by NASA includes five “themes” – biology and biogeochemistry of ecosystems and the global carbon cycle; global water cycle; atmospheric chemistry, aerosols, and solar radiation; oceans and ice in the climate system; and solid Earth science. The first four of these thematic areas are closely aligned with those of the US Global Change Research Program, facilitating coordination of research with other US science agencies. An integrative modeling activity helps bring the individual components together to achieve our Earth system science goals. This approach is implemented with significant attention given to promoting close linkages between the traditional Earth science disciplines; the Earth system science concept has been the driving paradigm of ESE over the past decade, and this conceptual approach will only expand in the coming decade.

1. INTRODUCTION

The mission of NASA's Earth Science Enterprise (ESE) is to develop a scientific understanding of the Earth system and its response to natural or human-induced changes and improve prediction capabilities for climate, weather, global air quality and natural hazards. The Earth science research program aims to acquire a deeper understanding of the components of the Earth system and their interactions. These interactions occur on a continuum of spatial and temporal scales ranging from short-term weather to long-term climate scales, and from local and regional to global scales. The Enterprise also seeks to provide accurate assessments of changes in the composition of the atmosphere, the extent and health of the world's forest, grassland, and agricultural resources, and geologic phenomena that lead to natural hazards.

The NASA Earth Science program is driven by the recognition of the societal importance of the natural variability of the planetary environment and the realization that humans are no longer passive participants in the evolution of the Earth system. The world's scientific authorities share this view broadly. Responding to severe droughts and floods that revealed societal vulnerability to climate variations, the World Meteorological Organization, the International Council of Scientific Unions (ICSU), and UNESCO initiated in 1979 the World Climate Research Program, an international effort to understand the physical basis of climate. In 1982, NASA proposed a scientific program to acquire the knowledge "to ensure continuing habitability" of our planet in the face of expanding human populations and activities. The International Geosphere-Biosphere Program (IGBP) was established by ICSU "to describe and understand the interactive physical, chemical, and biological processes that regulate the Earth's unique environment for life, the changes that are occurring in this system, and the manner in which they are influenced by human actions" (NRC, 1983). In 1988, the NASA Advisory Council charted a course for NASA's pursuit of Earth System Science (NASA, 1988).

The new scientific concept, Earth System Science, which emerged as the central paradigm of these national and international Earth Science programs is based on the recognition that: (1) the Earth can be understood only as an interactive system embracing the atmosphere, oceans and sea-ice, glaciers and ice-sheets, marine and terrestrial ecosystems, the land surface, and the Earth's interior; (2) new environmental problems are likely to arise, the solutions of which must draw on years of accumulated knowledge; and (3) science is a partner in national and international decision-making aiming to develop the potential to benefit society and to enhance economic security. There is no doubt that an integrated Earth system perspective would have eventually emerged as individual Earth science disciplines matured and global observing capabilities developed. However, a sense of urgency stemming from the observation of ozone depletion over Antarctica, evidence of widespread deforestation in the tropics, measurements of increased concentrations of carbon dioxide at Mauna Loa observatory, and model predictions of global climate warming led to the creation of the US Global Change Research Program (USGCRP) to "understand and respond to global change, including the cumulative effects of human activities and natural processes on the environment" (US Congress, 1990)..

NASA's contribution to the USGCRP is based on responding to this scientific vision with the unique capabilities which NASA brings to studies of the Earth system, and is designed to be part of the integrated national research program that constitutes the USGCRP. The use of the unique vantage point of space to study the entire Earth with technologically advanced remote sensing instruments forms the heart of NASA's contributions to this program. The global measurements which NASA provides will be

used as input for scientific studies designed to address the critical global change and Earth system science questions addressed in this plan. High performance aircraft and innovative combinations of instruments and airborne and/or balloon platforms also provide important means for obtaining needed information; development of improved capability in these areas is facilitated by NASA's technology development activities. NASA's observational strategy is designed to complement those of the other USGCRP agencies, especially the in situ research and operational networks of its partners. In some cases (e.g., vertical profiling of oceanic properties) the in situ data are the only sources of needed environmental information. The calibration and validation of NASA data makes critical use of these observational programs of the other agencies.

The end-to-end approach described in this plan will include NASA's contributions to the USGCRP modeling and data assimilation efforts, as well as the role of more regionally-focused process-oriented campaigns that help provide the knowledge basis for interpreting remotely-sensed observations, understanding Earth system processes, and representing them in the global models used by all the USGCRP agencies. Through partnerships with other USGCRP agencies, as well as NASA's counterpart agencies around the world, efforts will be made to assure that the measurement capability developed by NASA can be sustained and utilized to facilitate the continued improvement and availability of global Earth system observations, understanding, and forecast capability in the future.

NASA's Earth Science Enterprise aims to obtain a scientific understanding of the entire Earth system on a global scale by describing how its component parts and their interactions have evolved, how they function, and how they may be expected to continue to evolve on all time scales. The challenge is to develop the capability to predict those changes that will occur in the next decade to century, both naturally and in response to human activity. The strategic objective of the Enterprise is to provide scientific answers to the overarching question:

How is the Earth changing and what are the consequences for life on Earth?

In the words of the National Research Council/Committee on Global Change Research (NRC, 1999a), an important role of interdisciplinary Earth system science investigations is to prepare science for surprises. By definition, surprises cannot be fully anticipated, but they can be acknowledged as possibilities. A balanced research strategy in Earth system science should provide a broad enough observational basis to detect early manifestations of incipient unforeseen phenomena, and deep enough knowledge of the basic physical, chemical and biological processes involved to identify the likely causes. It is the special challenge for the NASA Earth Science strategy to cast the research net sufficiently wide (including laboratory and field studies as appropriate) to catch the unexpected, as well as respond to new contemporary science issues as they emerge.

The ESE has been seeking and will continue to seek the cooperation of national and international partners to maximize its investments' returns. In particular, the ESE actively cooperates with operational agencies to ensure the long-term continuity of key environmental measurements. To achieve this goal, NASA promotes the convergence of operational observation requirements with ESE's research data needs, and participates in the definition and development of precursor instruments and spacecraft technologies for future operational application missions. The ESE also aims to maximize synergism with related applied research programs conducted by partner agencies, especially the US Weather Research Program.

This document, which covers the period from 2000 to 2010, is one of several produced by the ESE to describe its activities. At the highest level is the Enterprise Strategic Plan (ESE, 2000a), while at the next level there is this document, describing the science research aims of the Enterprise and comparable documents representing its activities in the areas of applications, commercialization, and education (ESE,

2000b), and in technology (ESE, 1999). These three activities of the Enterprise work together to help assure that the advances in knowledge about the Earth system obtained through its research efforts achieve maximum societal benefit through their application by and communication to stakeholders in state and local governments, industry, and the general public. Synergy between research and technology activities ensures that the technology development program is driven by high priority science questions while its results are continually infused into the research program. Finally, close linkage between the research and education aims of the Enterprise ensures that tomorrow's Earth science practitioners have the opportunity to engage in state-of-the-art research while learning about the Earth system through the integrated perspective of Earth system science. Readers are encouraged to examine these other ESE documents in order to further understand these other aspects of the program.

Concurrent with the development of these plans is a longer-term effort to provide a vision for ESE's activities over the time period from 2010 to 2025. The longer-term, broader-scale effort is designed to more completely integrate the technology, research, and applications goals of the enterprise in a way that will allow for detailed end-to-end planning such that the scientifically and societally important questions posed can be answered, in particular with technological approaches specifically developed for that purpose. The resulting information will be provided to the scientific community and disseminated to the broader public through collaboration between NASA and its partners in the public and private sectors. For a fuller description of this longer-term planning process, the reader should examine the relevant document, which may be found at <http://www.earth.nasa.gov/visions/index.html>.

2. EARTH SYSTEM SCIENCE ISSUES

The key research topics studied by NASA's Earth Science Enterprise fall largely into three categories: forcings, responses, and the processes that link the two and provide feedback mechanisms. This conceptual approach applies in essence to all research areas of NASA's Earth science program, although it is particularly relevant to the problem of climate change, a major Earth science-related issue facing the countries of the world. The scientific strategy to address this immensely complex problem can be laid out in five steps or fundamental questions, each raising a wide range of cross-disciplinary science problems.

- *How is the global Earth system changing?*
- *What are the primary forcings of the Earth system?*
- *How does the Earth system respond to natural and human-induced changes?*
- *What are the consequences of change in the Earth system for human civilization?*
- *How well can we predict future changes in the Earth system?*

As will be seen below, each step in this logical progression of questions about Earth system changes necessarily touches upon practically all aspects of Earth system science. The questions also highlight the cross-disciplinary nature of global change research. This, by no means, downplays the significance of existing Earth science disciplines, nor the scientific importance of the complex interactive processes which govern the internal dynamics of individual Earth system components: the global atmospheric circulation and chemistry; the ocean circulation, the biogeochemical cycles; the mass balance of polar ice sheets and glaciers; terrestrial and marine ecosystems, and the solid Earth. Because of the importance and complexity of the processes involved in the internal dynamics of each component, and the scientific expertise accumulated in traditional Earth science disciplines that focus on these components, the most convenient organizational structure to plan the implementation of the ESE research program is an organization based on focused research themes, each addressing an individual component of the Earth system and key linkages with the other components. A final section on Earth system modeling completes

the plan, and shows how knowledge from research on individual Earth system components can be integrated to provide quantitative answers to questions on forcings, responses, and future changes of the total Earth system.

In establishing such a discipline-based structure, it is crucial that sufficient attention be paid to scientific issues at the boundaries between two or more traditional scientific disciplines. Indeed, these are the issues that led to the development of Earth system science as a discipline in its own right. This conceptual picture of the Earth as an integrated system is deeply imbedded within the ESE planning process and will be reflected in the research which is solicited and selected by the enterprise.

2.1 Earth's Natural Variability

The Sun and Earth constitute an exceedingly complex dynamic system that generates variations on all time-scales, from minutes to days in the case of tornadoes and other severe weather disturbances, to many millions of years in the case of tectonic phenomena and erosion that shaped the Earth's landscapes, and the biogeochemical processes that conditioned the Earth's atmosphere and oceans. One may distinguish three types of natural variability of the Earth system: each must be characterized and understood in order to make science-based predictions about the Earth's future evolution. The first type is the variability in the external forcing of the Earth by solar radiation and the extraterrestrial particles that reach the Earth and its atmosphere, such as those associated with solar proton events, as well as galactic cosmic rays and meteoric infall. Second is the variability generated within the Earth's interior, including the gravity and magnetic fields, the release of gases and particulate matter into the atmosphere from volcanic eruptions, geological processes such as earthquakes and erosion, as well as long-term effects associated with plate tectonics and motions deep inside the Earth. Third is the intrinsic variability of the Earth's atmosphere, hydrosphere, and biosphere, manifested in the interactive dynamics of the atmospheric and oceanic circulation, the global energy and water cycles, and the biogeochemical cycles. Even though variations in solar activity and volcanic eruption are, by right, natural phenomena, they constitute "external" forcing on the Earth climate system and the global environment, and will be considered in the next section (see Section 2.2)

The internal dynamics of the coupled atmosphere-hydrosphere-biosphere system are the principal source of natural variability. In the first place, the atmospheric circulation is by itself a chaotic dynamical system that constantly breeds new disturbances, from planetary perturbations such as the Quasi-Biennial Oscillations of the tropical stratosphere (which cycles over a period of about two years) to severe weather systems that generate heavy rain or snowfall as well as damage to human-built structures. Weather phenomena are not predictable on climate time scales (beyond one week or two), although their statistics are to some extent influenced by the more slowly varying aspects of the climate system, such as sea surface temperature. Since the latter do exhibit some predictability, the statistics may also have some degree of predictability. Weather phenomena do constitute a large background of random "meteorological noise", but nonetheless are important on account of their impact on society and their role in climate processes. Outside the tropics, the short-term variability of the atmospheric circulation is actually the main contributor to observed climate variations, and constitutes the background noise against which climatologists must strive to detect and quantify meaningful climate signals.

Most prominent among these longer-term signals are natural climate variations known as El Niño/Southern Oscillation (ENSO) phenomena, that occur at random intervals of a few years and last one to two years. The evolution of ENSO phenomena is governed by a known predictable mechanism, involving the two-way coupling of the (upper) tropical oceans with the global circulation of the atmosphere. Once initiated, the evolution of individual ENSO phenomena can indeed be predicted with a reasonable degree

of accuracy several months in advance. While the atmospheric manifestations of ENSO events are global, the region of most active interaction with the ocean is the tropical Pacific ocean, although significant ocean-atmosphere interactions occur elsewhere (e.g., Atlantic Ocean). Other similar but weaker modes of natural climate variability seem to exist on decadal time scales, but have not yet been fully characterized, much less explained and predicted (e. g. the Arctic Oscillation of the atmospheric circulation in the northern hemisphere, associated with the North Atlantic Oscillation). The complex linkages between atmospheric fluxes and ocean heat transport/storage lead to adjustments in the basin-wide circulation of the oceans on timescales from years to decades. Atmospheric variability and/or response to changes in ocean surface temperature affect surface winds, deep water formation, and ocean surface temperature and stratification. Considerable uncertainty remains, however, as to the mechanisms by which these longer-term variations modulate the shorter-term variations such as ENSO.

The significance of living systems as a factor in the Earth's natural variability, especially Earth's biogeochemical cycles, is a relatively recent discovery. The recognition of biotic factors as potential homeostatic controls of biogeochemical cycles has allowed for significant advances in our understanding of the natural metabolism responsible for the compositions of the atmosphere, oceans and sediments of planet Earth. It is estimated, for example, that the equilibrium global concentration of carbon dioxide in the atmosphere would be larger by about a factor 3 in the absence of the "biological pump" constituted by oceanic primary productivity. On the other hand, the CO₂ concentration would be smaller by about a factor 3 if the biological pump was operating everywhere at peak efficiency, compatible with available carbon.

2.2 Primary Forcings of the Global Earth System

The Sun is a mildly variable star that exhibits cyclical variations in its internal circulation and magnetic field, associated with minor changes in total radiation output but quite large changes in the ultraviolet part of the spectrum. Accurate measurements of solar radiation can only be made from space, due to the variable (and incompletely known) transmission of the Earth's atmosphere. Observed variations in total solar irradiance are believed to be too small to directly induce noticeable changes in the Earth's climate in the lower atmosphere. The larger variability in solar radiation at short wavelengths (UV and below) is known to affect the chemistry and composition of the stratosphere, with the magnitude of the effect increasing with altitude through the mesosphere and thermosphere. The possibility that these changes can induce sufficiently large changes in the troposphere to affect Earth's climate is a subject of active research. It is believed that, like similar stars, the Sun goes through occasional quiescent periods of low magnetic activity accompanied by a more substantial reduction in total radiation output. The most recent quiescent period occurred three centuries ago and may have been the cause of a general cooling observed in the Northern hemisphere during the "Little Ice Age". In addition, celestial mechanics impose quasi-cyclical variations in the parameters of the Earth orbit and rotation, thereby inducing major changes in the distribution of solar radiation incident upon the Earth surface and the timing of seasons, with still poorly understood consequences for the succession of glacial and interglacial climates (Milankovitch cycle).

Of a similar nature are changes generated by the motions of the Earth's interior, causing the accumulation of stress in the Earth's crust and occasional cataclysmic disturbances, such as earthquakes and volcanic eruptions. Gaseous emissions from the Earth's interior are, for the main part, a relatively quiet on-going process, notably on mid-ocean ridges where igneous matter from the mantle comes near the surface. Over geologic time ongoing gaseous emissions have helped determine the composition of the atmosphere. Major volcanic eruptions, on the other hand, can inject almost instantaneously very large

amounts of trace gases and particulate matter directly into the Earth's troposphere, as well as trace gases into the stratosphere. Large volcanic eruptions, like that of Mt. Pinatubo in 1991, have noticeable global effects on climate and atmospheric chemistry, principally the creation of an enhanced layer of sulfate aerosols in the stratosphere which contribute to a drop in ozone levels that can persist for several years. Such volcanic eruptions constitute natural climate modification experiments: the study of the transient response to the temporarily increased burden of particulate matter is a means to gauge the sensitivity of planetary climate to forced changes in Earth radiation balance.

As human populations have grown and become more technologically advanced, they have increasingly left their mark on the Earth's environment. Human-induced changes in land cover and land use, resulting from agricultural practices, forest exploitation and clearing, grazing by domestic animals, wetland loss, urbanization, combustion, and development of industrial and transportation infrastructures, continue at a rapid pace and their effects (whether inadvertent, considered as a consequence of economic development, or deliberately made to enhance the functions of natural ecosystems) can now be seen from space over the whole Earth. In addition to the obvious disturbance of natural ecosystems, such changes may cause noticeable and widespread impacts on regional climate and hydrologic regimes, local and regional agricultural and fisheries productivity, soil erosion, sediment transport, and significant changes in land surface albedo and aerodynamic roughness, as well as changes in the biogeochemical cycling of carbon, nitrogen and other important elements. The implications of these changes for sustainable food production and resource management as well as the maintenance of a healthy, productive environment are a very serious concern for societies.

In recent times, however, the most significant anthropogenic forcing of the planetary environment has been the modification of the composition of the atmosphere, leading to rising concentrations of a number of reactive and radiation absorbing gases that contribute to depleting the stratospheric ozone layer and to increasing the atmospheric greenhouse effect. Measurements at the Mauna Loa observatory and several other stations have documented a recent upward trend of about 0.4% per year in atmospheric carbon dioxide (CO₂), amounting to a 30% increase in global atmospheric concentration since the beginning of the industrial era. The buildup of atmospheric CO₂, driven by the combustion of fossil fuels along with deforestation and other changes in land use, is the largest contributor to the global increase in the greenhouse effect. Quantifying the fraction of CO₂ from anthropogenic sources that accumulates and remains in the atmosphere (about half of total emission) is, in itself, a very complex problem, considering that CO₂ fluxes from the combustion of fossil fuels and changes in land use are but a small fraction of the large natural fluxes between atmospheric, terrestrial ecosystem, and oceanic reservoirs. However, since the natural processes have been “in balance” even seemingly small perturbations in the sources and sinks due to human activity can lead to significant changes in atmospheric CO₂ levels.

Many human enterprises, from natural gas extraction to animal husbandry and the intensive cultivation of rice, generate yet poorly quantified amounts of methane. Methane gas in the atmosphere is more effective on a per molecule basis at absorbing infrared terrestrial radiation than CO₂. Thus, the oxidation of methane at the source or subsequently in the atmosphere effectively reduces the overall impact on the greenhouse effect. Many other trace gases produced by human industry, such as the by-products of fertilizer usage, chemical pollution from internal combustion engines, or the purposeful synthesis of special chemicals by industry (e. g. chlorofluorocarbon compounds) also add to the overall greenhouse gas burden. Ozone, sensitive to a variety of industry-produced compounds, also plays multiple climate forcing roles, through the absorption of solar ultra-violet radiation and terrestrial infrared radiation. The increase in tropospheric ozone over much of the world as a result of industrial activity has led to the contribution of ozone to radiative forcing being sufficiently important that it must be included in studies of climate forcing.

Another important forcing of climate is caused by natural and anthropogenic aerosols in the troposphere. The tropospheric aerosols produce a direct radiative forcing by virtue of scattering and absorbing solar radiation and an indirect forcing by changing the radiative properties of clouds. Radiative balance calculations suggest that the aerosol climate forcing can be comparable in magnitude but opposite in sign to that of anthropogenic greenhouse gases. However, the exact magnitude of the total aerosol forcing remains one of the largest unknown factors in climate research. It has even been speculated that the negative forcing of climate may have offset to a large degree the positive forcing due to the greenhouse gases, thereby temporarily masking much of the anthropogenic greenhouse effect.

Fires can effect large-scale, sometimes catastrophic, changes in land cover and terrestrial ecosystems, while creating large amounts of volatile pyrogenic materials, such as carbonaceous compounds and soot, that can disperse over very large atmospheric volumes and cause significant changes in the composition of the atmosphere and its radiative balance. The generation of fires and their ability to spread depends on climatological, ecological, and human factors (especially land use management). Fires also release trace gases and particulate matter into the atmosphere that can modify atmospheric chemistry and contribute to the greenhouse effect. Biogeochemical cycling in terrestrial ecosystems is profoundly affected by fires; nutrients can be made more available by fire and its after-effects on soils, they can be lost to the atmosphere in the form of trace gases or particulate matter, or they can be transported and deposited to distant ecosystems (both terrestrial and marine).

In addition, human activities induce environmental impacts on small, local spatial scales, including the withdrawal of water from ground water reservoirs, rivers or lakes, the release or disposal of toxic substances in the environment, the introduction of exotic species into local ecosystems, the fragmentation of habitats, the increase of sediment, nutrients, and pollutants in rivers and other aquatic ecosystems, and excessive demands on local biological resources (e. g. overfishing and overgrazing). Efforts designed to protect human communities (e.g., flood prevention, protection of local water supplies from salt inclusion) also will impact water availability and quality. The withdrawal of water results in enhanced evaporation, reduced river flow, and depletion of water reserves. The release of toxic chemicals results in disruptions of natural biogeochemical balances, stresses on the native flora and fauna, and even threats to human health. It is worth emphasizing that natural processes frequently connect large-scale and local forcings, and that the environmental impact of combined stresses may drastically exceed that from either one alone. Thus, it is important to understand the processes that connect human-induced disturbances and stresses on all scales.

2.3 Responses of the Earth System to Natural and Human-induced Disturbances

From a planet-wide perspective, observation shows that the primary indicators of the state of the Earth system vary from year to year and continue to evolve over periods of decades and longer. Long-term trends, in addition to inter-annual variations, are observed in the global atmospheric composition and circulation, Earth surface temperature, the global water cycle and total rainfall, the duration, frequency and severity of weather and hydrological phenomena, the ocean circulation and distribution of ice on Earth, global carbon cycle and total carbon storage in the Earth's oceans and terrestrial biosphere, the distribution and extent of global land cover, and the thickness of the global ozone layer. Establishing the existence of such trends against the background of geographic differences and transient fluctuations is a technical challenge, requiring full use of the resources (precision and global coverage) of modern observing techniques. In this regard, satellite observations have given us a powerful means to collect the required information systematically, globally, and under fully traceable conditions (notably, consistent sensor calibration).

The problem remains, however, of attributing the observed changes and trends to individual or combinations of causal (forcing) factors. The answer to this problem lies one step deeper in the basic physical, chemical, geological, biological, and social processes that control these planetary-scale changes and long-term trends. The basic processes are often mutually reinforcing or, to the contrary, restraining, and combine to constitute feedback mechanisms that amplify or moderate the response to primary disturbances and forcings.

Prominent among these mechanisms are the coupled variations in atmospheric temperature, water vapor, and clouds that govern radiation transfer through the atmosphere and changes in the global radiant energy budget of the planet. A rise in temperature is accompanied by an increase in atmospheric water vapor and its contribution to the greenhouse effect, thereby amplifying the primary forcing that caused the elevation of temperature in the first place. The role of clouds is much more complex, as different types of clouds can induce opposite net effects on the planetary radiation budget. The principal effect of low-lying, dense, and very bright water clouds is to cool the atmosphere by reducing the amount of solar radiation absorbed by the planet, whereas the presence of relatively thin and semi-transparent ice clouds at high-altitude primarily enhances the absorption of terrestrial infrared radiation and warms up the lower atmosphere. Also important is the role of clouds in moistening and/or drying the upper troposphere, as water vapor in that region of the atmosphere, has a potentially large, but incompletely understood, impact on the greenhouse effect and climate.

The formation of clouds is closely associated with the development of weather systems; purely dynamical changes in atmospheric flow will influence the distribution of cloudiness, the radiative balance of the planet, and rainfall distribution, even without any obvious change in global mean atmospheric temperature or humidity. Much improved knowledge of basic cloud processes and the life cycle of cloud systems is needed to predict how clouds might change in the future as a result of change in the atmospheric circulation and thermal structure. In general, a fundamental objective is the understanding of the relationship between climate change and the frequency/intensity of weather disturbances, which play a disproportionately large role in atmospheric transport and mixing, cloud system development, energy transformation, and precipitation.

The health and primary productivity of marine and terrestrial ecosystems are sensitive to changes in climatic conditions as well as the availability of nutrients and other environmental controls. Productivity is governed by the amount of incident solar radiation, the availability of water and atmospheric carbon dioxide; the stability of temperature within the relatively narrow range suitable for life; and the availability of required nutrients in terrestrial soils, brought from the deep by ocean upwelling, or transported by the atmosphere from another region of the Earth. The primary productivity of the biosphere is one of the principal processes governing the Earth's carbon cycle on annual to decadal time-scales. The changing phenological state and health of plants likewise govern the rate of exchange of CO₂ and water between the atmosphere and vegetation, thus controlling, at the same time, the storage of carbon and the loss of water by terrestrial vegetation. In this respect, vegetation plays a major (moderating) role in the hydrological cycle, surface water storage, run-off, infiltration, and regional hydrologic regimes in general. Similarly, in the ocean, phytoplankton contribute significantly to spatial variations in CO₂.

From an Earth system perspective, the global carbon cycle is governed by the global distribution of marine and terrestrial ecosystems and the impact of their biological activity on the global environment. In particular, it is essential to relate the intensity of biological activity to the controlling (radiative, meteorological, hydrological, biogeochemical) factors on a global basis, including the cycling of other chemical elements (e.g., nitrogen) that are critical to the development and functioning of ecosystems.. Remote sensing provides the opportunity to gather much of the needed global data on both the

distribution of ecosystems and relevant forcing factors, but converting these observations to information on global environmental impact requires sufficient knowledge about basic processes and the function of ecosystems. Process-level knowledge is acquired primarily through *in situ* studies, often in the context of major field campaigns which allow detailed analysis of key processes and controlling factors.

Likewise, it is essential to understand the global water cycle, both as the central element of atmospheric climate change and a critical environmental factor that influences the other components of the Earth system. In particular, the availability of soil moisture and the transition of frozen soil to thawed conditions have a controlling influence on the productivity of terrestrial ecosystems. Conversely, the phenological progression of vegetation from dormant, to growing, to mature stages, governs the ability of vegetation to draw water from the ground, transfer it to the atmosphere, and thereby influence surface climate and the partitioning of radiant energy between latent and sensible fluxes. The global measurement of soil moisture, snow-water equivalent, freeze-thaw transitions, stage of water in rivers and inland water bodies, and river flow could significantly enhance our knowledge of the global water cycle..

It has been shown beyond doubt that halogenated compounds produced by human industry are the primary cause of global decline in the amount of stratospheric ozone. This includes both the decreases in global ozone amounts and the much larger decreases in high latitude spring observed in the Antarctic and, to a lesser extent, in the Arctic region.. The phenomenon is governed by the complex chemistry of atmospheric ozone, involving numerous chemical species and free radicals, and controlled by climatic conditions that allow very low temperature to form and persist for long periods of time. Conversely, the distribution of ozone and some other absorbing molecules control radiative heating and stratospheric climate (circulation and temperature).

This linkage between chemistry and climate provides opportunities for complex and non-linear interactions. Most importantly, low stratospheric temperatures permit the formation of cloud and aerosol particles, which can have significant implications for both atmospheric chemistry and for radiation. Detailed understanding of the conditions under which these particles form is important if accurate forecasts can be made in an atmosphere with altered temperature distributions. Similarly, changes in the dynamics of the tropopause region could affect the transport of water vapor and other trace gases from the troposphere into the stratosphere and thus affect aerosol formation, chemistry, and radiation in the stratosphere. Understanding how stratospheric water vapor might change in the future requires basic understanding of the dynamics of the tropopause region and troposphere-stratosphere exchange mechanisms. Finally, any change in meteorological activity that drives the stratosphere and affects the stability of the polar vortices will have significant impacts on chemistry, especially the partitioning of chlorine and nitrogen between compounds which are more and less active in ozone depletion. Conversely, atmospheric model simulations show that changes in stratospheric circulation and thermal structure may propagate downwards and affect tropospheric climate. The factors that control the stability of the polar vortices and their relationship with tropospheric circulation must be understood to assess the implications of possible future variations.

Microphysical and chemical processes, as well as atmospheric transport, mixing, and removal, govern the formation of aerosols in the lower troposphere from a variety of surface sources and/or precursor gases, their number and size distribution in the atmosphere, their composition and optical properties, and ultimately their direct effect on the planetary radiation balance. Satellite observations provide the potential to help characterize the global distribution and, to some extent, the properties of aerosol particles in the atmosphere. However, variability in aerosol types, height, chemical composition and optical properties means that satellite observations alone cannot provide all the needed information on aerosols. A variety of observational data from *in situ* sampling, airborne and ground-based optical remote

sensing, advanced satellite instruments, and detailed modeling studies of aerosol processes will be needed to understand the relationship between aerosol composition, height distribution, and optical properties under a sufficiently broad range of aerosol types and geophysical conditions. Even more complex cloud-dynamical and microphysical phenomena are initiated by aerosol condensation nuclei which may induce significant changes in the particle size distribution of low-lying clouds and cause indirect climate forcing by altering the optical properties of these clouds. Sufficiently detailed knowledge of the processes by which aerosols affect cloud formation and properties must be obtained on a global scale so that these indirect effects can be realistically represented in models.

The formation, transport and eventual melting of sea-ice at high latitude involve complex ice and water properties, polar weather phenomena, and the oceanic circulation. Over 10-13% of the surface of the ocean, sea-ice acts as an insulating layer that blocks exchanges of water and energy with the atmosphere. The high albedo of raw and snow-covered ice further reduces the absorption of solar radiation and tends to maintain the surface cold, with direct consequences on polar atmosphere stability and weather. The formation of sea-ice is accompanied by the rejection of concentrated brine that increases the salt content of the ocean locally and promotes the sinking of cold, high-salinity surface water to great depth. Conversely, the advection and melting of relatively fresh sea ice lowers the salinity of the ocean and blocks deep water formation, thus inducing a complex coupling between sea ice, deep water formation, and decadal climate variability. The measurement of ocean surface salinity can dramatically increase our knowledge of the conditioning of ocean waters by air-sea interactions and their impact on deep-water formation.

2.4 Consequences of Changes in the Earth System for Human Societies

Statistically meaningful but small changes in the global distribution of Earth system properties, such as mean surface temperature or sea-level pressure, would not draw much attention if we did not foresee that relatively small variations in the global environment can entail changes of much greater significance in regional weather, productivity patterns, water resource availability, and other environmental attributes. We already know, for example, that La Niña climate episodes, manifested by cooling of surface waters in the eastern tropical Pacific ocean by a few degrees Celsius, are associated with more active hurricane seasons in the Atlantic basin, featuring more frequent and generally stronger tropical cyclones than normal years. Conversely, El Niño warm ocean water episodes have dramatic impacts on regional marine productivity and broader climate patterns, including the frequency of Atlantic hurricanes.

There is little doubt that other global climate changes can also induce significant differences in the frequency, duration and intensity of weather disturbances, such as severe storms and rainfall, floods and droughts. In particular, the acceleration of the global water cycle due to warmer temperatures is expected to produce heavier rains and larger water run-off, especially in winter, but also faster evaporation and generally drier conditions in summer, thus amplifying the contrasts between dry and wet seasons, and exacerbating chronic water shortfalls in arid regions. Global climate warming observed during the last few decades appears to have already resulted in a lengthening of the growing season at mid- to high-northern latitudes, and may be contributing to desertification in the sub-tropics (IPCC, 1998). Changes from snowfall to rainfall would also significantly affect the annual patterns of stream flow (higher in winter, earlier peak flow, lower summer flows), which can have dramatic impacts on fisheries as well as irrigation needs.

Sea-level rise, resulting from the thermal expansion of ocean waters and mass loss from continental glaciers and ice sheets, is a gradual but important phenomenon of concern to all coastal countries, especially low-lying atolls. Sea level rise is accompanied by a redistribution of coastal materials, beach

erosion, flooding of freshwater wetlands and the invasion of coastal aquifers by salt water. The societal implications of sea level rise are significant. It is estimated that a 0.5 m rise in sea level would cause a loss of about a third of US wetlands (with corresponding loss of the biogeochemical recycling capability and ecosystem goods and services, such as fishery productivity, from such wetlands).

Ecosystems may have difficulty adapting to relatively rapid changes in the physical environment. Climate change is thus becoming an additional stress that may combine with other stresses, e. g. invasion by exotic species or increased frequency and/or extent of fires, to alter drastically the structure and composition of established ecosystems and lead to their impoverishment or ultimate disappearance in favor of a more tolerant ecosystem. An example of a particularly sensitive ecosystem that cannot easily "migrate" to a more favorable region is that of tropical corals, now subject to bleaching and death almost everywhere. Deforestation and other ecosystem disturbances caused by human activities can result in irreversible changes, such as loss of species (biodiversity), and other undesirable effects such as increased erosion, loss of essential nutrients, decreased agricultural productivity, and accelerated rainwater runoff from watersheds. It is vitally important to understand the consequences of such changes for sustained agriculture, forestry, and fisheries and the continued provision of ecosystem goods and services that are valuable to human societies. It will be especially important to understand the controlling factors when sustainable production is successfully achieved while the ecosystem is under pressure from population growth and/or land use change

The growth in human population and the increasing levels of industrial activity, especially in developing countries are likely to combine and lead to dramatically increased gaseous and particulate matter pollution of the atmosphere in some parts of the world (e. g. south and east Asia and Latin America), with attendant consequences for human health and ecosystem productivity. There is evidence that pollutant gases from densely populated regions, notably carbon monoxide, sulfur dioxide and oxides of nitrogen, can be transported over very large distances by the atmospheric circulation, thus causing air quality problems in regions far removed from the sources. It has been recognized recently that the transport of pollutants in the troposphere takes place principally within thin layers that may extend over very long distances. Such long-distance transport creates risks of increased pollution far away from the sources, for instance pollutants from Asian sources over the west coast of the United States. Surface air quality data have given support to such connections. Such long range transport is also capable of transporting nutrients over long distances (for example, from the Saharan desert to the subtropical Atlantic Ocean or the Amazon) and thus play an important role in ecosystem productivity and biogeochemical cycling for a broad range of nutrients.

Reductions in stratospheric ozone amounts have been shown to lead to increases in the amount of biologically damaging ultraviolet radiation that reaches the Earth's surface. The harmful effects of UV radiation on humans include skin cancer, cataracts, and immune system suppression. UV radiation can also have significant impacts on ecosystems, especially the phytoplankton that are a critical element in the oceanic food chain. Effects of UV increases are of special interest at high latitudes where the largest decreases in ozone have taken place.

2.5 Prediction of Future Changes in the Earth Climate and Global Environment

The overarching purpose of Earth system science is to develop the knowledge basis for predicting future changes in the coupled physical, chemical, geological, biological, and social state of the Earth and assessing the risks associated with such changes. Of particular interest are changes in physical climate on the time scale of a human generation, e. g. changes in the composition and chemistry of the atmosphere,

and changes in biogeochemical cycles and primary productivity. It is clear that to predict the long-term evolution of the Earth system, a good understanding of the way that humans will interact with the environment must be obtained and represented in the models used for simulations.

A first step towards predicting the future of the Earth system is building a capability to simulate realistically the present state and short-term variations of the global environment. This includes defining accurate and realistic representations of all relevant forcing factors and their role in the system, and the physical, chemical, geological, and biological processes involved, including especially the processes which couple the different components of the system: the global atmosphere; the world oceans; land and sea ice; marine and terrestrial ecosystems; and the Earth's landscapes and surface geology. The only practical strategy for such a complex task is to develop predictive skills, focusing necessarily on suitably defined sub-systems of the complete Earth system for verification against observations.

Frequent experimental data assimilation and prediction cycles, made possible by the daily acquisition of global atmospheric, oceanic, and surface observations, are instrumental in verifying and improving the representation (prediction) of realistic weather and weather-related phenomena in climate models. On longer time scales, realistic representation of atmosphere-land hydrology and atmosphere-ocean interactions, as well as the full three-dimensional nature of the ocean, become essential. Experimental predictions of significant interannual climate fluctuations, for example ENSO phenomena clearly require information on the physical state of the oceans. Simulation of transport, mixing and transformations of trace gases and aerosols in the Earth's atmosphere is an attractive proposition whenever suitable environmental and meteorological data are available to verify model predictions. Predictions based on atmospheric chemistry or biogeochemical cycling models may be tested against the current distributions of relevant compounds in the Earth's atmosphere, oceans, land, and biosphere. Ecological research is striving to acquire the same type of information on marine and terrestrial ecosystem dynamics to test model simulations of the recovery of these ecosystems from known disturbances or stresses.

Predictive models can similarly be used in a retrospective mode to simulate past changes for the purpose of testing hypotheses about the possible causes of these changes and verifying the models' capability to reproduce the full range of observed variability. The latter is especially important to gauge our capability to assess the risk for rapid changes and possible surprises in the evolution of the Earth system. The use of mathematical analogs to simulate past changes, that are documented directly in the historical record or indirectly by various existing paleoclimatic indicators, is also a powerful means to identify key linkages between the components of the Earth system.

The objective, however, is to build on the confidence gained in simulating current or past environmental conditions and apply these skills to the prediction of future long-term changes. Such predictions are usually intended to assess the potential consequences of various assumed scenarios for the future evolution of relevant forcing factors: emissions of active chemical compounds and greenhouse gases from various sources, changes in the global cycles of carbon, nitrogen, and other important elements, changes in land use and water management, population growth, economic development, etc. It is important that the modeling tools used for prediction have the capability, including spatial resolution, needed to address regional impacts of predicted global changes.

3. SCIENCE PRIORITY CRITERIA

The Earth system science issues outlined above are remarkable for the diversity of topics, the complexity of the interactions, the multiplicity of spatial scales (from microscopic to global), and the range of time periods (conceivably, from minutes to millions of years). A great number of scientific questions have been posed by the nation through NRC reports (e. g. *Global Environmental Change: Research Pathways for the Next Decade*, NRC, 1999a) and the USGCRP. In fact, the focused attention placed on global change research over the last decade has energized the Earth sciences and greatly enhanced both our understanding of Earth system processes and the range of new scientific questions to be addressed. Investigating the full range of these scientific questions exceeds the capabilities allowed by current resources. No agency or even group of USGCRP partner agencies has the means to address all the important scientific questions posed within the breadth of Earth system science. This makes the issue of program prioritization all the more critical. Optimum return from NASA's investments in Earth observations and research, measured in terms of objective information and answers provided to issues relevant to society, will be obtained when scientific value is the leading factor for prioritization.

Establishing research priorities becomes a major challenge when priorities cross a number of different disciplines, each embracing a large set of scientific questions. The challenge facing the ESE is to balance competing demands in the face of limited resources and chart a program that addresses the most important and tractable scientific questions and allows optimal use of NASA's unique capabilities for global observation, data acquisition and analysis, and basic research. To this end, choices need to be made between many projects, all of which are important, timely, and ready to succeed. Most significant from a strategic perspective are the choices between different but equally promising candidate space flight missions or measurement systems.

Thus, NASA's selection of priorities involves both scientific needs and implementation realities. Scientific considerations are paramount and start the prioritization process. These considerations determine what science questions, and ultimately which research projects (modeling, observations, process studies), should be pursued. Purely scientific considerations are followed by considerations of science-related context (e.g., benefit to society, mandated programs), followed in turn by implementation considerations. The latter, such as technology readiness, tend to impact the order in which science projects are pursued and the final shape they may take. These practical considerations often result in some feedback and iteration of project selection.

Science Priority Criteria



Science Return
Benefit to Society
Mandated Program
Appropriate for NASA
Partnership Opportunity
Technology Readiness
Program Balance
Cost/Budget Context

Implementation Priority Criteria

The list of criteria is not ordered by importance in all cases; rather, it is presented in a logical order of procession as project concepts are conceived and matured. It is worth noting that the details of applying these criteria may vary, especially given the nature of the question being investigated and the mission potentially being initiated. These criteria are described in the following paragraphs.

Scientific Return

The scientific return of research activities, such as discussed in the plan, is judged in term of the perceived significance of the scientific problem being addressed in the grand scheme of Earth system science, and anticipated advances toward providing definitive answer(s). Scientific return is often high for innovative investigations that break into heretofore unexplored scientific territory. In other instances, major scientific advances are achieved only through systematic analysis of vast bodies of observational evidence, as is often the case in the study of complex systems like the Earth. Best scientific return is generally obtained when research and observing program initiatives are conceived and designed to address specific science issues or questions. To ensure full scientific return, the ESE recognizes the need for a balanced research program that provides not only unique space-based and airborne observational capabilities, but also the means to analyze the data, compare to surface-based measurements and state-of-the-art models, and conduct end-to-end research projects that can deliver conclusive answers to specific Earth system science problems.

Finally, scientific priority also stems from the logical progression in approaching a complex scientific problem. Identifying the significant elements of variability in the Earth system and trends in forcing factors provides a necessary foundation for deeper insight in response mechanisms. Likewise, investigation of the consequences and the development of robust prediction methods require a priori knowledge of the operative processes. The program implemented by the ESE will represent an appropriate balance between the different steps of this progression. The potential for amplification of the response is an element of this choice (e. g. the positive feedback associated with changes in the distribution of atmospheric water vapor). As regards climate change assessments, for example, the largest sources of uncertainty have been identified by the Intergovernmental Panel on Climate Change (IPCC, 1996).

Benefit to Society

In addition to scientific merit, one of NASA's strategic goals is to develop useful information, products, and capabilities for society. NASA research is expected to contribute to society in several ways. As governments, businesses, and individuals make decisions about their future plans, *scientific information* about the environment and potential changes will be an important element of the decision process. NASA science should contribute to the flow of this information, especially in issues such as climate variations and trends, ozone depletion, and the state of the biosphere.

The observational *data products* obtained primarily for scientific purposes can also be used for the conduct of current operations by individuals, businesses, state and local agencies, land use planners, and resource managers, among others. Not only must the data be made available to these constituencies in an appropriate form and a timely fashion, but a data system must be available that facilitates the sharing of this information. An element of choice in selecting research programs is the potential for continuing infusion of relevant data for applications purposes.

Experimental observation and modeling capabilities developed by NASA for scientific purposes can be used by operational agencies for practical applications. There is particular interest in scientific investigations that could enhance the accuracy and range of *weather forecasts*, e. g. through the introduction of new data sources, or improvements in predictive models and data assimilation methods. Close cooperation with NOAA and other forecasting agencies is desired to assure that the results of NASA science are incorporated into operational systems and products.

Mandated Programs

A special case of research programs beneficial to society, mandated activities include legislative requirements to maintain a research, monitoring, and technology development program related to the surveillance of atmospheric ozone for atmospheric chemistry research and monitoring, as specified by NASA's Authorization Act and the Clean Air Act. NASA is also required to report to Congress and the Environmental Protection Agency every third year on the status of knowledge of atmospheric ozone and the abundance of ozone-depleting substances in the atmosphere. More recently, the Enterprise has been directed to increase its research effort on the global carbon cycle. Finally Congressional directions, received through the budgeting process, must also be met.

Appropriate for NASA

NASA shares with other USGCRP partners an interest in fundamental studies of the basic processes that govern the Earth system, diagnostic studies of recent and past data records, and model simulations/predictions of global changes. At the same time, effective use of resources requires that the ESE's science strategy be focused on research projects that allow optimal use of NASA's unique capabilities. Compared to the range of investigations embraced by the entire USGCRP, NASA's Earth science program emphasizes measuring changes in forcing parameters, and documenting the natural variability of the Earth system and responses to forcings, especially through space-based measurements that can provide global coverage, high spatial resolution, and/or temporal resolution, in combinations which cannot be achieved by conventional observational networks.

The *Research Pathways* report (NRC, 1999a) formulated a wide range of research imperatives and scientific questions that require investigation across the field of Earth system science. Choosing among all potentially important research questions is a judgment of scientific value. In the context of NASA's Earth science research program, the principal scientific priority criteria are the spatial scale, temporal duration, and magnitude of the phenomena being investigated, as well as anticipated return in term of reducing the uncertainty on potential changes in the Earth system.

Research questions that address Earth system dynamics at ***large regional to global scales*** are those of greatest interest for the ESE. Questions that involve smaller scale changes that have the potential to be of global significance if aggregated over a sufficiently large number of areas, are also relevant to ESE. This is particularly true for regions where only limited conventional (non-space) observations are available (e. g. the atmosphere over the open ocean and polar regions; continental ice sheets). For example, ESE's atmospheric chemistry research has been focused on global scale chemical processes rather than local air quality (which is typically the responsibility of regulatory environmental agencies).

Likewise preference is given to the study of phenomena and processes that may induce lasting changes in the Earth system, typically ***seasonal and longer period responses***, as well as changes that are irreversible in the foreseeable future. Understanding and predicting fast processes (e. g. the development of weather systems, trace gas emissions) may be essential in order to quantify longer-term average impacts. While forecasting individual environmental phenomena is not a primary ESE objective, further developing experimental prediction of specific events (e. g. weather disturbances) that can be verified by observation is a fundamental research tool for understanding changes in climate and the global environment (e. g. mean displacement in storm tracks). At the process level, priority is given to those processes that have the potential to induce ***large impacts*** and/or are the root of large uncertainty in the overall response of the Earth system.

NASA has a very strong commitment to the use of its observational data in scientific research, and invests in the development of models and global data assimilation systems that can be used for the analysis and interpretation of observations from NASA programs and other relevant observing networks, as well as for the development of improved forecasting capability related to answering the questions

posed in this plan. NASA's earth science research program also has a robust sub-orbital component, which is focused on improving our understanding of processes needed to understand, interpret, and model remotely sensed observations, as well as to contribute to the calibration and validation of the space-based observations. Innovative combinations of observing instruments and platforms are used in this component of the program.

Partnership Opportunity

The ESE research program is conducted within a larger national and international context. This implies both opportunities for task-sharing with partner agencies, and the responsibility to seek optimal coordination of mutually supportive programs of these national and international partners. In particular, NASA has been actively seeking the cooperation of operational agencies in the US (through the National Polar-Orbiting Operational Environmental Satellite System, NPOESS) and elsewhere to ensure the long-term continuity of key environmental measurements in the long term. To achieve this goal, NASA will promote the convergence of the operational observation requirements of partner agencies with ESE research data needs for systematic observations, share the cost of new developments, and develop precursor instruments and spacecraft technologies for future operational application missions. NASA will also encourage the continuing involvement of scientific investigators in the calibration and validation of operational measurements, the development of more advanced information retrieval algorithms, and the analysis of operational data records. From this perspective, the potential for serving operational needs or commercial applications is a priority criterion for ESE programs, since such applications imply the potential for cooperation with relevant government agencies or data purchase from commercial sources.

Interagency and international partnerships are also important methods for maximizing the scientific value of any research activity while minimizing costs. The need for partnerships in process-oriented field measurement activities is crucial, especially when investigators' access to particular regions of scientific interest is needed. For space-based measurements, partnerships provide the opportunity for leveraging additional contributions onto those that would be made by NASA, and allow for benefiting from the technological and scientific skills resident in other agencies and countries, as well as access to information needed for validation under a broad range of biological and geophysical conditions. Partnership opportunities will typically be encouraged in all relevant solicitations as long as they are consistent with national policy objectives such as export control of sensitive technology. Commercial partnerships also provide the opportunity for NASA to obtain needed data or services, and NASA has committed to working with the private sector to avoid duplicating capability that already exists in it.

Technology Readiness

For observation projects in particular, a key criterion in determining the timing and order of selection is the readiness of the relevant technology. In some cases, as with soil moisture measurements, additional technological investments were required over the past and current years in order to demonstrate the possibility of making this measurement from space. For instance, lidar wind measurements were possible a decade ago, but only at an unacceptable cost for development and operations. Recent and ongoing work indicates the potential for design of a space-based system at a cost comparable to current programs, and perhaps even implementation as a commercial data purchase. NASA implements technology development programs relevant to each stage of the instrument maturation process (e.g., components, instrument design, flight demonstration). Parallel programs in spacecraft and information technologies are pursued to assure overall mission feasibility.

Program Balance

The hallmark of NASA's Earth science program is the synergy between different classes of observations, basic research, modeling, and data analysis, as well as field and laboratory studies. In particular, when engaging in pioneering research about complex scientific issues, the ESE recognizes the need for complementary remote sensing and in situ measurements. Nonetheless, the strategic decisions that define the ESE program in the long term are those which affect the space flight mission element, involving the longest lead-time and largest investment of resources. From both a programmatic and a scientific research strategy perspective, the ESE distinguishes three types of space flight missions: systematic observation missions, exploratory missions, and operational precursor or technology demonstration missions. The identification of these categories represents a significant departure from the original architecture of the Earth Observing System, which combined studying basic processes, assembling long-term measurement records, and introducing innovative measurement techniques. The distinction between these classes of missions facilitates a sharper definition of primary mission requirements, and clearer selection criteria, ultimately leading to a shorter development cycle and more cost-effective implementation. Priority criteria will be considered separately for the research and analysis program and the three categories of missions.

Basic Research and Data Analysis

The intellectual capital for both the planning and exploitation of Earth system observations is vested in an robust research and analysis program. Research and analysis is the conceptual source of Earth system science questions, and strategies to address them. The research program is at the origin of new scientific ideas and emerging research approaches, supports the early development of innovative observing techniques (including both instruments and the linkage of instruments with platforms) and processing algorithms, organizes field tests, and generally charts the path for scientific and engineering developments that enable future advances. It assures the linkage between global satellite observations, ground-, aircraft- and balloon-based observations, including those used for studies of long-term system evolution and shorter-term process-oriented studies, and the computational models used to provide both a framework for interpretation of observations and a tool for prediction. Through focused calibration/validation activities, it helps assure the development of consistent, integrated, and well calibrated data sets, especially those that involve multiple instruments, observational platforms, and observing techniques. The ESE actively supports the scientific use of such multi-instrument/multi-platform data sets for looking at long-term system evolution, and such use frequently serves as the most stringent test of the quality of a scientific data set. The existence of a close tie between research and data-set oriented activities provides the critical "feedback loop" that assures continued focus on maintaining the highest quality data sets possible over long time periods.

Altogether, the research and analysis program brings fundamental research to bear on key Earth science issues, and lays the interdisciplinary groundwork for linking these research efforts. As a general rule, all NASA Earth science research and analysis projects are implemented through a competitive selection process based on responses to solicitations issued by NASA (Announcements of Opportunity, NASA Research Announcements, and Cooperative Agreement Notices) and a scientific peer review.

Systematic Measurements

The need for long-term continuity of critical Earth observations has been repeatedly emphasized by the global change research community. Systematic measurements of key environmental variables are essential to specify changes in forcings caused by factors outside the Earth system (e. g. changes in incident solar radiation) and to document the behavior of the major components of the total Earth system. Following the recommendation of the *Research Pathways* report (NRC, 1999a): "Priority must be given to identifying and obtaining accurate data on key variables carefully selected in view of the most critical scientific questions and practically feasible measurement capabilities".

Systematic is not necessarily synonymous with continuous measurement. Gaps in systematic measurement time series may be tolerable for scientific investigations when short-term natural variability or calibration uncertainties between successive discontinuous records do not mask significant long-term trends. In principle, ESE plans for systematic observations aim for measurement continuity, based on best estimates of observing system lifetimes and time for replacement. On the other hand, the ESE's mission implementation plan does not provide for instantaneous (in-orbit) replacements in case of premature sensor or spacecraft failure. Overlapping measurement records from successive sensors are required, however, when no ground-based observation can provide an independent calibration standard (e. g. solar irradiance). It is essential that requirements for systematic observation programs be reviewed and focused on a minimum set of essential measurements.

A particular challenge for NASA and other agencies occurs when systematic observations are transitioned from those obtained in a research-oriented program to those that will be obtained in an operationally-oriented one (NRC, 2000). Such a transition is expected to take place over the course of this decade for a number of environmental parameters, especially given the planned initiation of NPOESS near the end of the decade. In particular, assuring the ability of data from operational entities for studies of long-term global change questions requires the very accurate knowledge of absolute and relative calibration of relevant instruments, the upgrading of retrieval algorithms (including those that may make use of ancillary data sets not normally used in the operational algorithms), and the periodic reprocessing of data sets needed to assure consistency for the construction of the required multi-instrument/multi-platform data sets. ESE expects to work closely with NPOESS to facilitate such developments, and where need is demonstrated, to support such activities through this transition period so that the ability of the earth science research community to answer the questions posed in this plan (especially those of long-term variability) can be sustained.

Exploratory Measurements

Exploratory missions which can yield new scientific breakthroughs must be a significant component of the ESE's program, in conformity with the strategic mission of NASA to promote research and development. Each exploratory satellite project is expected to be a one-time mission that can deliver conclusive scientific results addressing a focused set of scientific questions. In some cases, this may involve measuring several related parameters to allow closure tests to be carried out. In other cases, an exploratory mission may focus on a single pioneering measurement that opens a new window on the behavior of the Earth system. Included in this class of missions are small, university-led missions which seek to train the next generation of scientists at the same time scientific information is obtained. No

commitment for long-term measurement is made with this class of mission, although it is possible that the results of an exploratory project could lead to introducing a new systematic measurement or transition to an operational application program.

Operational Precursor & Technology Demonstration Missions

The ESE recognizes that requirements for more comprehensive and accurate measurements place increasing pressure on operational environmental agencies and require major upgrades of existing operational observing systems. In order to enable such advances, NASA will invest in innovative sensor technologies and develop more cost-effective versions of its pioneer scientific instruments that can be used effectively by operational agencies. The plan identifies several operational precursor or "bridging" missions that will lead to future operational deployment in low Earth orbit or geostationary orbit during the next decade, principally within the framework of the NPOESS and GOES programs. Active participation of operational agencies in the definition and development of the new systems, and their commitment to transition to operational status, are essential for the success of such operational precursor developments. In this regard, the determination of the partner agency to continue a new observation when technological readiness is demonstrated is a major element of choice in NASA's decision to invest in operational precursor missions. Continued close working relationships between ESE and its partners are clearly needed to drive initiatives in this area.

Data Management and Distribution

The satellite, process study, and modeling and data assimilation programs of ESE have the capacity to produce unprecedented amounts of data, the value of which is only maximized with their full use by the international Earth Science research and applications communities. This volume of data, together with the diversity of the user community, provide a significant challenge to the enterprise because of the need to assure both prompt and easy access by users with varying degrees of knowledge and expertise and the ability to maintain the quality of the data over long time periods. A successful data and information systems and services program includes both planning for scientific data quality refinement, allowing for periodic reprocessing and data stewardship, providing for archive integrity and continual infusion of new technology (including storage media). Further, it is recognized that Earth science research will use more than just ESE data (for instance, observations from operational space- and ground-based environmental measurement systems) so data systems that are interoperable with those of other providers of critical Earth Science data are needed.

To assure this availability, ESE has made a major commitment to data processing, archival, storage, and access, and expects to continue this in the future. Through this commitment, the enterprise endeavors to make data available to the science and applications research communities at minimal costs. The method of data system implementation is expected to evolve, however. Prior plans, focused on logically centralized computing and storage systems developed based on earlier technology, are now being followed by those that take full advantage of more recent developments in computing technology and networking to provide for a framework linking the user to products and services within more heterogeneous distributed data systems. An operative principle in the ESE's treatment of its data is to assure continual involvement of interested scientists who have a scientific stake in the data being managed and archived.

Completing the Cycle – from Scientific Results to Answers to Questions

The ESE research program, including its observational and modeling component, provides a vast amount of scientific information of various types – basic knowledge of processes, large observational data sets,

model calculations being among them. An important activity of the ESE research and analysis program is to help the scientific community digest and synthesize the results, and advance from an increase in specialized scientific knowledge to well-documented answers to the broader questions posed in this plan. NASA will actively support the development and implementation of an appropriate process to "complete the cycle" in which questions are formulated, scientific studies are carried out, specific answers are developed to the extent possible; organization of and/or participation in specific assessments on a periodic basis will be used to evaluate progress towards resolving the science questions outlined in section 4. NASA will also re-evaluate its overall strategy periodically and involve the scientific community in the re-evaluation process.

The nature of the scientific enterprise is that initial results will be reported through the peer-reviewed scientific literature and presented at scientific meetings. The sheer volume of scientific findings and, in many cases, the diversity of ideas, imply that a synthesis effort is needed to communicate the information usefully outside the scientific community. Several pathways exist to produce such syntheses. The assessment process, in which groups of scientists work to synthesize their knowledge in a particular area, is perhaps the best established means to make the connection between research results and the answers sought by the sponsors of research. In such assessments, the scientific community comes together to answer not only questions such as "What do we know?" but also, and perhaps equally importantly, "How well do we know what we think we know?"

International assessments, such as the ozone change assessments carried out for the World Meteorological Organization and the United Nations Environment Programme or the climate change assessments carried out for the Intergovernmental Panel on Climate Change have a long history of accomplishment and continue to play a seminal role in the development of the relevant disciplines. Other, more specialized, assessments are undertaken to resolve (or progress toward resolution of) a specific scientific issue. The recent report from the National Research Council on *Reconciling Observations of Global Temperature Change* (NRC, 1999b) is a noteworthy example of such a study. NASA will facilitate such consultations of the Earth science community to evaluate the effectiveness of its research strategy.

Through the US Global Change Research Program, NASA is strongly engaged in the National Assessments on Climate Change process. These assessments have both regional and sectoral foci, and serve to bring together not only the scientific research community, but also users within federal, state, and local governments, as well as regional agencies, the private sector, and non-governmental organizations. The assessments provide a particularly critical way to try to provide clear answers to climate variability, consequences, and prediction issues at the spatial and temporal scales that matter directly to environmental decision-makers.

NASA will help enable a strong participation of the ESE research community in assessment activities and values their involvement, as well as the use of ESE data in such assessments. In all cases, the aim of the assessment is to express the outcome of the scientific synthesis effort in a form that is useful to decision-makers in government, industry, and the broader society. The evolving needs of these users, and the outcome of the assessments themselves, serve to refine the scientific questions, thus completing the cycle and providing new directions for research.

Cost/Budget Context

In the end, the set of research projects of all types must be mapped into the overall budget context constraining NASA's Earth Science Enterprise. This is not a fixed parameter; the budget level itself is partly a function of the scientific rationale and societal benefit that a balanced Earth Science program can

provide. Once established, the negotiated (or anticipated) budget envelope becomes a criterion that may drive an iteration for many projects back up the criterion ladder to some level.

4. NASA EARTH SCIENCE RESEARCH PRIORITIES

The five fundamental science questions define a logical progression in the study of global change, but each question covers a range of topics too broad to serve as a guide for program implementation. For this purpose, more specific research questions need to be formulated and prioritized. These second-tier questions, summarized in Table 4.1, are discussed in significantly greater detail in the subsequent chapters of the plan and ranked within each of the five fundamental questions on the basis of the criteria enunciated in section 3, principally scientific return and benefit to society. The major factors to be considered in prioritizing the questions, discussed in more detail for each question, are the amplitude of the impact of the particular variations, forcings, or responses on the Earth system, the likelihood of a breakthrough; the lead time for reaching a conclusive answer or developing a new prediction capability; and the significance of potential consequences or applications for society. When it comes to implementing missions, other criteria, such as technology readiness and partnership opportunities will become increasingly important, as will the cost/budget context in which mission development can take place and program balance across the enterprise.

As noted earlier, the details of the implementation of the criteria may vary for different types of missions. For example, in implementing systematic missions, timeliness is likely to be a much more significant driver than in the case of exploratory missions, as continuity of a particular environmental parameter may be at stake. Similarly, partnership arrangements will be critical in formulating potential operational precursor missions, but may not be a driving issue in the formulation of exploratory missions, except to the extent to which partner contributions allow for improved science relative to NASA's financial commitment. The announcement of opportunity (AO) or other procurement vehicle that might be used for a particular mission solicitation, will reflect the criteria and their relative priorities.

Nonetheless, it should be emphasized that the Earth is a strongly interactive system and that conclusive results cannot be expected by either focusing exclusively on a single component (e.g., variability) at a time or addressing these in a purely sequential manner; progress must be made in all areas, although the balance of resources applied towards individual components in the program may vary over time. Recognizing this need for progress in these multiple areas the five fundamental science questions are not prioritized. Indeed, progress in all five research areas is critical if we are to develop a predictive capability for the Earth system based on robust scientific understanding of natural variability, human forcings, and responses.

The research expertise that NASA brings to answering the questions posed in this plan is strongest in the disciplines that individually and collectively constitute the field of Earth system science, as well as several areas underlying science (e.g., physics, chemistry, ecology, applied mathematics and computing, data and information systems). It is clear, however, that developing answers to all of these questions (especially those in the areas of consequences, as well as several areas of forcing, such as land use change) will require a broad range of scientific expertise, including that of the social sciences, with which NASA's interactions have historically been more limited. Closer ties between NASA and the social science research community are being developed through NASA's Land Cover and Land Use Program as well as NASA's applications efforts (described in the ACE plan), and the development of interactions between the respective research communities will be encouraged. NASA will also draw on the social science research expertise available through other agencies of the USGCRP.

In posing the specific questions, key parameters for which observations are required will be identified and summarized in tables (one table for each major question area). It is important to recognize that not all the data sets needed for the key parameters must be derived from NASA projects. Indeed, many come from operational activities of other agencies, and include both space-based and those from other (ground-, ocean-, and balloon-based) platforms, while others may come from research networks provided by other agencies. Included in the tables are lists of parameters tied back to the most relevant question, details of implementation, and considerations associated with several of the criteria described in the previous section (technical readiness, partnership potential, including that for transition to operational agencies).

Table 4.1: Hierarchy of Science Questions

Overall: *How is the Earth changing and what are the consequences for life on Earth?*

- ***How is the global Earth system changing?(Variability)***
 - How are global precipitation, evaporation, and the cycling of water changing?
 - How is the global ocean circulation varying on interannual, decadal, and longer time scales?
 - How are global ecosystems changing?
 - How is stratospheric ozone changing, as the abundance of ozone-destroying chemicals decreases and new substitutes increases?
 - What changes are occurring in the mass of the Earth's ice cover?
 - What are the motions of the Earth and the Earth's interior, and what information can be inferred about Earth's internal processes?
- ***What are the primary forcings of the Earth system? (Forcing)***
 - What trends in atmospheric constituents and solar radiation are driving global climate?
 - What changes are occurring in global land cover and land use, and what are their causes?
 - How is the Earth's surface being transformed and how can such information be used to predict future changes?
- ***How does the Earth system respond to natural and human-induced changes?(Response)***
 - What are the effects of clouds and surface hydrologic processes on Earth's climate?
 - How do ecosystems respond to and affect global environmental change and the carbon cycle?
 - How can climate variations induce changes in the global ocean circulation?
 - How do stratospheric trace constituents respond to change in climate and atmospheric composition?
 - How is global sea level affected by climate change?
 - What are the effects of regional pollution on the global atmosphere, and the effects of global chemical and climate changes on regional air quality?
- ***What are the consequences of change in the Earth system for human civilization?(Consequences)***
 - How are variations in local weather, precipitation and water resources related to global climate variation?
 - What are the consequences of land cover and land use change for the sustainability of ecosystems and economic productivity?
 - What are the consequences of climate and sea level changes and increased human activities on coastal regions?
- ***How well can we predict future changes to the Earth system?(Prediction)***
 - How well can weather forecast duration and reliability be improved by new space-based observations, data assimilation, and modeling?
 - How well can transient climate variations be understood and predicted?
 - How well can long-term climatic trends be assessed or predicted?
 - How well can future atmospheric chemical impacts on ozone and climate be predicted?
 - How well can cycling of carbon through the Earth system be modeled, and how reliable are predicted future atmospheric concentrations of carbon dioxide and methane by these models?

4.1 Earth System Variability and Trends

Systematic measurements provide the fundamental knowledge basis for diagnostic studies of Earth system changes, as well as investigating the mechanisms underlying these changes (see 4.3 below). The *Research Pathways* report (NRC, 1999a) defined the goal of global change research as that of "obtaining accurate [observational] data on key variables carefully selected in view of the most critical scientific questions and practically feasible measurement capabilities". The objective is to identify significant changes in the states of the principal components of the Earth system: the atmosphere and oceans, terrestrial and marine ecosystems, atmospheric chemistry, ice sheets, and the Earth's topographic surface. To this end, the observational strategy will be focused on a limited set of independent properties that each characterize an important component of the system. In implementing observations needed for systematic measurements, a focus on long-term precision, calibration information and validation over the lifetime of the mission are critical if separate data sets are to be combined into the multi-instrument-multi-platform data sets necessary for quantitative studies of long-term global change.

The study of the Earth's interior plays a supporting role in the research strategy, as the interactions of Earth's internal processes with the other four components are less significant on relatively short (10-100 year) time-scales. Systematic observations of solid Earth parameters provide a foundation for many Earth system science investigations, notably the precise shape of the Earth's surface, the gravity field and its variations, and the geodetic reference frame for navigation and GPS-based remote sensing systems.

As noted in the previous section, not all required observational parameters need come from NASA projects. This is especially true for systematic measurements, in which observations of global meteorological and oceanic parameters from the space-based and in situ measurement network of operational agencies are the primary data sets for some parameters. For others, plans have already begun to transition such operations from research-oriented organizations, such as NASA, to operationally-oriented ones, such as NPOESS. Observational parameters for which systematic measurements are most needed are summarized in Table 4.2.

- (1) **How are global precipitation, evaporation, and the cycling of water changing?** A statistically meaningful but relatively small rise in global mean temperature (with significant regional differences) has been observed at the surface of the Earth during the last century, particularly the last two decades. Surface warming implies a rise in the temperature of all or part of the atmospheric column, an increase in atmospheric water content, and changes in atmospheric circulation that are manifested by a global pattern of warming and cooling. Such changes would not draw much attention if we did not foresee that relatively small variations in the global environment can entail changes of much greater significance in regional weather, ecosystem productivity, water resource availability, and other essential attributes of the environment. The unambiguous determination of long-term changes in the cycling of water through the atmosphere in the presence of significant shorter-term variations (e.g., seasonal, interannual, including that associated with quasi-periodic phenomena such as El Niño and the Quasi-Biennial Oscillation) presents a challenge to both the measurement approaches used to provide the needed record and the statistical approaches used to try to establish significance.

Atmospheric temperature implicitly determines the large-scale atmospheric flow, including dynamical instabilities that are at the origin of weather phenomena. *Atmospheric water vapor* is the principal vehicle of the atmospheric energy that drives the development of weather systems and the source of precipitation. Further, water vapor is a strong absorber of terrestrial radiation; increased

atmospheric moisture associated with warmer air has a powerful amplifying impact (positive feedback) on the greenhouse effect. Global temperature and moisture profile measurements are obtained routinely by operational environmental satellites, but the existing operational measurements do not provide the accuracy and consistency required for climate research. NASA investments in advanced sensor technology offer several alternative means (at various stages of technological readiness) to fulfill these scientific requirements. Improved observations will also be of direct benefit for weather forecasting applications.

Global precipitation is the principal indicator of the rate of global water cycle, and can also be used effectively as an input for numerical weather forecasting. Together, the atmospheric water content and global precipitation rate determine the residence time of water in the atmosphere. Precipitation data, obtained routinely by a worldwide network of land-based rain gauges, show evidence of increasing rainfall rates in some regions. In other regions, notably oceanic regions in the tropics, knowledge of precipitation rates has been poor due to the limited observational base. Clearly, the existence of a global trend can only be established on the basis of global rainfall observations. Space-based global observations have been significantly improved by the on-going Tropical Rainfall Measuring Mission and have now reached the degree of reliability needed for systematic measurement.

Changes in **soil moisture** over continents have a major impact on terrestrial life and human needs, as precipitation and evaporation govern the runoff of rainfall to the river system, the replenishment of water resources, and the amount of soil moisture available for plant growth. Conversely, soil moisture is a controlling factor of evaporation from the land surface (or plant-mediated evapotranspiration), and the principal indicator of large-scale changes in surficial water reserves. Changes in surficial soil moisture or "soil wetness" affect the dielectric properties of the ground and can be detected remotely by active or passive microwave measurements. Before surface soil moisture can be considered as ready for systematic space-based measurement, it should be successfully demonstrated. NASA will coordinate with all interested agencies in investigating soil moisture measurements and their potential implementation

(2) How is the global ocean circulation varying on interannual, decadal, and longer time scales?

The circulation of the Earth's oceans is, together with the atmospheric circulation, the mechanism by which the Earth redistributes to the whole planet the excess energy received in the tropics from the Sun. The ocean's enormous capacity for temporarily or permanent storage of heat is a major stabilizing factor of climate. On the other hand, changes in ocean circulation would have significant impacts on global climate. The rate and extent to which the oceans can take up excess energy absorbed by the planet will place a limit on atmospheric heating and climate warming. The ocean circulation also controls marine productivity and modulates the global biogeochemical cycles (notably, the global carbon cycle).

Sea surface temperature is the principal governing parameter of air-sea interaction and a primary indicator of global climate change. The **extent of sea-ice** over polar oceans is also a sensitive indicator of climate change, as the annual cycling of the ice cover is determined by a finely tuned balance between radiant heat loss, heat exchanges with the ocean and atmosphere, and the absorption of solar radiation during summer (the latter being strongly dependent upon the rapidly changing optical properties of dry or melting snow and ice). Recent observational evidence indicates not only a significant decreasing trend in the extent of sea ice over the Arctic ocean, but also a decrease in mean sea-ice thickness. The permanent disappearance of summer sea ice in the Arctic is a distinct possibility under plausible climate warming scenarios, and would have a major amplifying effect on global warming at high northern latitudes. Both sea surface temperature and the extent of sea ice are routinely determined by operational observing systems.

Knowledge acquired in the past about *ocean currents* and *sea level* was derived from *in situ* oceanographic and tide gauge observations available from a limited set of coastal stations or oceanographic cruises. Only space-based observation can provide the global coverage, spatial resolution, and sampling frequency necessary to capture the full range of variability in the global ocean circulation. Space-based measurements of the height of the ocean surface, relative to the reference surface of the Earth gravity field, and of the friction created by ocean surface winds provide first-order information on the ocean circulation. Altimetry also reveals changes in the sub-surface temperature structure and heat content of the ocean, as was observed in the tropical Pacific before the inception of the 1997-98 El Niño event, thus allowing reliable prediction of this climate event.

Accurate knowledge of the Earth's *gravity field* and *the Earth's center of mass* is also necessary to translate the raw satellite altimetry data into useful dynamic information (height above the reference surface for gravitational potential or "geoid"). New observing techniques being developed now have the potential to raise our knowledge of the geoid to a new level of accuracy, comparable to the precision of altimetric measurements. In the future, it is anticipated that further technical advances will enable detecting transient changes in the Earth gravity field, effectively measuring the gravitational signature of changes in mass distribution at the surface of the planet. Such gravity measurements will enable mapping the time-dependent distribution of water masses (in effect ocean bottom pressure) and learn directly about total ocean transport.

- (3) **How are global ecosystems changing?** Variations and trends in the productivity, composition, and health of terrestrial and marine ecosystems are a significant aspect of Earth system variability. In addition to the production of food and fiber, ecosystems govern the changes in the Earth's biogeochemical cycles, especially the carbon cycle, and modulate the cycling of water over land through changes in storage capacity and evapotranspiration. Peaks in marine primary productivity (blooms) usually occur when oceanic motions bring nutrient-rich waters into the well-lit upper oceans. Such events often dominate the downward flux of organic carbon. Terrestrial primary productivity varies more predictably with the seasons over much of the Earth's land surface, initiating photosynthesis and growth after the thawing of frozen soils or with the onset of a rainy season, peaking when environmental conditions are optimal, and declining when temperatures drop below freezing or with the onset of seasonal drought. Annual primary productivity does vary significantly from one year to the next in response to a variety of environmental factors, such as changes in nutrient supply and extreme or variable weather events, as well as year-to-year meteorological variability, including that associated with quasi-periodic phenomena such as El Niño. Satellite observations provide the only means to obtain a global view of the Earth's ecosystems, their spatial distribution, extent, and temporal dynamics, and to estimate changes in *primary productivity*. This information is needed globally, at moderate spatial resolution (hundreds of meters to a kilometer) and high frequency (daily or near-daily), and can be derived from the analysis of moderate-resolution multispectral image data obtained by operational and research satellites. The connection between the parameters most directly measured by satellites (e.g., chlorophyll concentration or a vegetation index) and those desired (e.g., primary productivity) requires significant validation effort.
- (4) **How is stratospheric ozone changing, as the abundance of ozone-destroying chemicals decreases and new substitutes increases?** It is well established that the primary cause of the stratospheric ozone depletion observed over the last two decades is an increase in the concentrations of chlorofluorocarbons (CFCs) and other halogen-containing hydrocarbons of industrial origin. The depletion has been significant, ranging from a few percent per decade at mid-latitudes to greater than

fifty percent seasonal losses at high latitudes, notably the annually recurring Antarctic ozone hole, as well as smaller, but still large, winter/spring ozone losses observed recently in the Arctic.

The abundance of chlorine in the stratosphere, the largest contributor to ozone depletion, is now reaching a peak value nearly five times greater than the natural level. This leveling off of stratospheric concentration comes several years after the peak in total chlorine abundance occurred in the Earth's troposphere. The time difference is consistent with our understanding of the delay required for transport from the Earth's surface to the stratosphere. This reversal in the evolution of chlorine demonstrates success in the implementation of the Montreal Protocol on Substances that Deplete the Ozone Layer and its amendments. Future decrease in chlorine abundance will be quite slow, however, due to the long time scale (in excess of 100 years for some chemicals) for the removal of trace gases by natural processes. The concentrations of other ozone-depleting substances, notably bromine compounds, are not all decreasing. In fact, some observed changes are in apparent conflict with the Montreal Protocol restrictions on production.

Major scientific issues remain, related to both the susceptibility of the ozone layer to further destruction by active halogen during the next decades of peak vulnerability and the timescale for the expected recovery of stratospheric ozone during the 21st century. The scientific challenge is that ozone amount is affected by numerous other factors than chlorine and bromine, notably stratospheric aerosol loading (which can dramatically increase following volcanic eruptions), the 11-year solar activity cycle, changing concentrations of other trace gases such as methane, nitrous oxide, and water vapor. Meteorological variability is also a factor; perhaps 20-30% of the mid-latitude ozone loss may be associated with change in atmospheric dynamics, the origin and nature of which are not clear.

Accurate and consistent long-term observations of *ozone distribution* (both total column and vertical profiles), together with the key parameters governing its abundance, are needed to arrive at a scientifically robust diagnostic of stratospheric ozone recovery and understanding of transient variations. Very accurate absolute radiometric calibration and the maintenance of long-term instrument stability are critical requirements to document long-term variability. Although accurate knowledge of trends in tropospheric ozone is highly desirable from a scientific point of view, the limited availability of global data (especially the satellite data record) at the present time places significant constraints on its usefulness to establish such trends. As global data on the vertical distribution of tropospheric ozone become increasingly available, such trend studies may begin to be possible.

- (5) **What changes are occurring in the mass of the Earth's ice cover?** The Earth's ice cover acts as an important indicator of the state of the global climate system, while at the same time exerting controls on climate that remain poorly defined. Polar ice sheets, grounded over Greenland and the Antarctic continent, constitute the largest reservoir of fresh water on the planet, corresponding to about 2% of the mass of the global oceans. Change in the mass balance of these ice sheets would result in major changes in the global volume of ocean waters and global sea-level. Airborne surveys of the Greenland ice sheet show little elevation change over most of the interior of the ice sheet above 2000 meters in height, but some areas of significant elevation change - predominantly thinning around the coast.. Assessing the rate of change of the much larger Antarctic ice sheet is a major challenge, which can only be met through repeated space-based surveys of *ice surface topography* at the appropriate measurement accuracy of a few centimeters. NASA is currently developing a space-based lidar altimetry system that will enable surveying of the Antarctic ice sheet to 86°S. Smaller ice caps and glaciers, while individually minor contributors to global sea level change, have contributed collectively to perhaps one third of observed sea level rise over the last century and are important indicators of regional climate.

- (6) **What are the motions of the Earth and the Earth's interior, and what information can be inferred about Earth's internal processes?** Changes in the Earth interior induce small, but nevertheless significant changes in the shape, rotation, and wobbling motion of the Earth. Knowledge of these relatively small changes is essential for a variety of applications (such as establishing the reference frame for precision geodesy, GPS satellite navigation, and ocean altimetry) as well as for understanding the dynamics of the Earth's interior. Monitoring the Earth's internal motions relies on a diversity of surface-based and space-based observations, particularly satellite lidar tracking, radio telescope observations, magnetic field measurements, and precision Earth gravity mapping. This information is being acquired through a worldwide cooperative effort, with a strong participation of NASA. The research strategy is a long-term cumulative effort: each new observation, obtained when a cooperative opportunity arises, adds to the precision of the reconstructed picture of the Earth's interior.

Table 4.2 Key Observations for Identifying Earth System Variations and Trends

Parameter/ Question	Implementation Details	In Situ Measurements	Technical Readiness	Operational Potential thru 2010	Partnership Potential
Atmospheric Temperature (V1)	Passive Sounding	Radiosondes (NOAA, WWW, NASA, NDSC)	Excellent	NPOESS requirement	EUMETSAT coordination
	Active Sounding (GPS)	Global GPS network	Full demonstration needed	NPOESS requirement	EUMETSAT coordination
Atmospheric Water Vapor (V1)	Passive Sounding	Radiosondes, Ly- α , μ wave (NASA, NOAA, WWW)	Satisfactory	NPOESS requirement	EUMETSAT coordination
Global Precipitation (V1)	Requires 6-8 satellite constellation for time resolution	Rain gauges, weather radar (NOAA, WWW)	Demonstrated by TRMM and passive μ wave imagers	TBD; only passive μ wave currently planned	Excellent – several needed
Soil Moisture (V1)	Spatial resolution and ability to penetrate vegetation required	neutron probes, lysimeters (USDA, USGS, FAO)	Very large real or synthetic antenna to be demonstrated	Highly desired; subject to operational viability	Likely with European Space Agency
Ocean Surface Topography (V2)	Prefer orbits that avoid tidal aliasing	Tide gauges (Global Geodetic Network)	Demonstrated. Development needed for denser coverage	Under study by NPOESS	Continuation of current partnerships likely
Ocean Surface Winds (V2)	Active / passive μ wave technique required	ships, buoys (NOAA, WWW)	Demonstrated by NSCAT and Seawinds	NPOESS requirement may be fulfilled	Seawinds and follow-on cooperation with Japan
Sea Surface Temperature (V2)	Both IR and microwave needed for all-weather observation	ships, buoys (NOAA, WWW)	Excellent	NPOESS requirement	EUMETSAT coordination
Sea Ice Extent (V2)	Microwave sensors needed for all-weather measurements	Ships, airborne reconnaissance (Navy, USCG, NOAA)	Excellent	NPOESS requirement	NASDA cooperation
Terrestrial Primary Productivity (V3)	1 km or better resolution global coverage required	Crop, forest inven. (USDA, FAO, NSF, GTOS)	Excellent	NPOESS requirement	EUMETSAT coordination
Marine Primary Productivity (V3)	Very precise inter- satellite calibration is essential	NASA-SIMBIOS time series studies	Demonstrated	Partially provided by NPOESS	Cooperation with Japan, Europe possible
Total Column Ozone (V4)	Long-term high accuracy needed for trend studies	Dobson, Brewer, FTIR, UV/VIS (NASA, NOAA)	Excellent	NPOESS requirement	EUMETSAT coordination
Ozone Vertical Profile (V4)	Good vertical resolution needed near tropopause	Ozonesondes, lidar, μ wave, IR, (NASA, NOAA)	Excellent	NPOESS requirement	International coordination
Ice Surface Topography (V5)	Excellent vertical resolution and accuracy needed for mass balance studies	GPS (NASA, NSF)	ICESat lidar altimetry demonstration	Not currently an operational requirement	Coordination with European radar altimetry satellite
Gravity Field (V6)	Requires high precision	Geodetic networks	GRACE demo. pending	DOD interest in precise geoid	Possible
Terrestrial Reference Frame (V6)	Derived mainly from ground observation and precision satellite tracking	SLR and GPS networks	Excellent	Multi-agency infrastructure	Multi-national ground network
Motions of the Earth's Interior	Inferred from mult. measurements --	SLR, GPS, VLBI networks,	Excellent	Multi-agency infrastructure	Excellent for exploratory

(V6)	space/ground based	magnetometer obs.			mission(s)
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4.2 Primary Forcings of the Earth System

Observed variations and trends in the Earth system are the combined result of natural variability and forced changes. In order to identify the origin of these changes, a necessary condition is to quantify the primary forcings induced by the Sun or human activities on the Earth system. Two kinds of human actions have passed the threshold of global significance, changes in the composition of the atmosphere and changes in land cover and land use. Variations in the radiation output of the Sun, and internally generated changes in the Earth's topographic surface are superimposed on these anthropogenic forcings. Systematic and accurate measurements of all forcing factors are indispensable if one is to attribute the observed changes in the global environment to specific causes. The key observational parameters required for characterizing forcings of the Earth system are summarized in Table 4.3.

- (1) **What trends in atmospheric constituents and solar radiation are driving global climate?** The primary external forcing affecting the Earth is change in the Sun's total energy output. Variations in total solar radiation per unit of Earth's surface (*total solar irradiance*) are currently quite small (less than 0.2% over an 11 year solar cycle, with relatively small day-to-day variations associated with sunspots, etc.), but total solar irradiance may have been substantially lower during the recent solar activity minimum which coincided with the general cooling of climate in the 17th century. Changes in solar output could have important consequences for the Earth's climate, so maintaining an accurate record of total solar irradiance is a necessary foundation for Earth system science. Given the small temporal variations and the difficulty in assuring accurate in-space calibration of these measurements, overlap between successive instruments is a fundamental requirement.

The Sun's energy output is considerably more variable in the ultraviolet part of the spectrum. The shorter the wavelength, the larger the variability – ranging from some 5% over a solar cycle at the wavelengths involved in stratospheric ozone production, to a factor 2 in the hydrogen Lyman alpha region of the spectrum that affects the mesosphere and thermosphere. Assessments of the evolution of ozone variations and upper atmosphere temperatures must account for the solar cycle induced variation in their distribution. The extent to which the resulting larger chemical and thermal variations in the stratosphere and above can be propagated downwards and then influence climate in the lower atmosphere is a current research problem. Continued long-term monitoring of spectrally resolved *solar UV irradiance* is therefore required to address issues of ozone and climate.

Stratospheric aerosols that result from large volcanic eruptions can significantly cool the Earth's surface, as has been demonstrated by several volcanic eruptions (most recently, that of Mt. Pinatubo in 1991). A large volcanic eruption can raise the stratospheric aerosol loading by a factor of 100 globally, and decay towards background levels is slow (several years). Background aerosol levels may also be raised by aviation and other industrial activities; continued observations of stratospheric aerosol amount are needed to characterize both the long-term and shorter-term variability. Tropospheric aerosols, on the other hand, can either cool or warm the atmosphere depending on their properties. The spatial and temporal variation of tropospheric aerosols is sufficiently large that frequent global space-based observations are needed if their presence is to be adequately characterized. Global observations of *total aerosol amount* and stratospheric *aerosol vertical profiles* are required to monitor this important climate forcing globally. Obtaining complete information on aerosol properties, including sufficient information on optical, radiative, and chemical properties that can be used in models remains a research challenge, however, requiring a combination of advanced space-based measurements together with *in situ* airborne and ground-based remote sensing observations.

Long-lived trace gases such as carbon dioxide, methane, nitrous oxide, and chlorofluorocarbons are all important for trapping infrared radiation in the atmosphere and contributing to global warming.

The major observational requirement for most of these is to monitor their total concentrations is *in situ* measurements of surface level concentrations of these trace gases. Ozone is another radiatively important trace gas in the troposphere, and has sufficient spatial and temporal variation that its concentration must be known throughout the troposphere. On the other hand, estimating the sources and sinks of these trace constituents at the surface of the Earth requires frequent and dense observations of spatial and temporal variations in their concentrations, as well as knowledge of the natural, agricultural, and industrial processes that are most directly responsible. The first measurements of the distribution of total methane are only now becoming available. Corresponding measurements for carbon dioxide, of enormous scientific interest for improving our knowledge of the carbon cycle, will require the development of new measuring technologies. Models will play a critical role in converting observations into the source-sink information that is desired.

- (2) **What changes are occurring in global land cover and land use, and what are their causes?** Biophysical phenomena and human activities that drive changes in land cover and land use include changes in agricultural practices, natural and human-triggered fires, drought and flooding, forest exploitation and clearing, grazing by domestic animals, and urbanization. Each of these phenomena can cause considerable disturbance or stress in natural and managed ecosystems, and consequently the whole Earth system. In combination, these changes in land cover and land use have grown to become a major factor of landscape modification, affecting ecosystem productivity and biogeochemical cycles; regional climates and hydrologic regimes; and soil erosion and sediment transport. Land use management practices, in particular, can create “sharp boundaries” that might not exist in nature, and the environmental effects of these will need to be understood. Documenting these changes and investigating their causes requires observations at the spatial scales of the disturbance or stress factors themselves, often on the order of tens of meters. Understanding the origin of the changes may require consideration of detailed socio-political factors operating in a given region. The observational requirements are for periodic global inventories of ***land cover and land use***, derived from observations repeated once or a few times per year. This information is obtained from systematic global multispectral mapping of the land cover at spatial resolution of a few meters. The potential of meter-class resolution (“hyperspatial”) mapping is being investigated for sharper diagnosis of causal factors and likely future trends.
- (3) **How is the Earth’s surface being transformed and how can such information be used to predict future changes?** The current knowledge of the dynamics of the Earth's interior is far from being advanced enough to enable specific and accurate prediction of hazardous geological events, such as earthquakes and volcanic eruptions. The scientific objective, at this time, is to acquire a fundamental understanding of the landscape-forming processes which explain the history and evolution of geologic systems, in order to lay the basis for assessment of potential natural hazards. Recent advances in land surface geodesy allow measuring the deformation of the Earth crust over time periods much shorter than earthquake or volcanic eruption cycles. In order to arrive at useful assessments of geological risks, it would be necessary to characterize these ***deformation and stress accumulation*** phenomena over a complete cycle (e. g. before, during and after seismic events). This cannot be done directly, but the information can nevertheless be assembled by combining observations from a number of sites at different stages in their own cycle. The main sources of information are, at the local scale, dense arrays of precision GPS receivers anchored in the ground and, at the regional scale, the “interferometric” analysis of synthetic aperture radar (SAR) image data.

Table 4.3 Key Observational Requirements for Determining Primary Forcings on the Earth System

Parameter / Question	Implementation Details	In Situ Measurements	Technical Readiness	Operational Potential thru 2010	Partnership Potential
Total Solar Irradiance (F1)	High absolute accuracy, overlap of successive records required	global surface networks (BSRN, WRDC, SURFRAD)	Excellent	NPOESS requirement	Possible
Solar UV Irradiance (F1)	Spectral resolution & good radiometric accuracy req'd	USGCRP UV network, NDSC (multiagency)	Excellent	NPOESS measurement planned	Strong history of cooperation
Stratospheric Aerosol Distribution (F1)	Good vertical resolution and large dynamic range required	Lidar, backscatter-sondes (NASA, NOAA, NSF)	Excellent	NPOESS meas. possible but resolution is problematic	Possible
Total Aerosol Amount (F1)	Global coverage over ocean and land needed	AERONET, USDA network, NOAA/BSRN, DOE/ARM	Excellent	NPOESS requirement	Possible
Aerosol Properties (F1)	Need in situ and ground-based measurements	AERONET, NOAA/CMDL, airborne aerosol spectrometers	Further development needed for space measurement	Not currently an operational requirement	Possible, important for ground-based measurements
Surface Trace Gas Concentration (F1)	Ground-based measurements fulfil requirements	NASA AGAGE, NOAA flask network and CO ₂ meas.	Need simpler instruments with better time resolution	NOAA flask sampling network, NASA AGAGE	Helps support ground network
Volcanic Gas & Ash Emissions (F1)	Global observation of ash and gas plumes	In situ optical calibration	Further progress needed to characterize tropospheric constituents	Significant on account of impact on aviation	Possible
Fire Occurrences (F2)	Global observation of infrared and vis/near-ir; hyperspectral for fuel load	Aeronet (NASA), burn scar inven. (USFS, int'l.), In situ optical calib.	Excellent	NPOESS EDR application	NPOESS EDR application
Trace Gas Sources (F2)	CO ₂ column mapping is greatest priority	Flask network (NOAA), Ameriflux (DOE, USDA, NASA), FluxNet	Technical developments needed for exploratory mission	Not currently an operational requirement	Possible
Land Cover/ Land Use Inventories (F2)	High spatial resolution required (few tens of meters)	Land Cover Maps (USGS), Veg. Inventories (DOI, USDA)	Excellent, need to reduce cost	Not currently; working with USGS	Commercial data purchase likely
Surface Stress and Deformation (F2)	Special focus on active earthquake and volcanic regions	Regional GPS networks, geological obs.	Excellent	Joint support of ground arrays by local agencies	multi-national support for ground arrays

4.3 Earth System Responses and Feedback Processes

Two scientific strategies are conceivable to study the responses of the Earth system to natural and human-induced forcings. The first is the holistic approach, based on analyzing observed changes in the Earth system taken as a whole. The second is the analytical approach, based on detailed characterization of elementary processes involved in the response mechanism, and simulation of the interplay among these processes with mathematical models. Both methods actually aim at the same objective, that of identifying the signatures of individual forcing factors and modes of natural variability in the response of the Earth system. The first approach relies on the same systematic measurements and observational records as required to document natural variability and trends (see 4.1 above). The second approach requires specific new observations that enable in-depth studies of the operative processes. As elementary processes usually involve shorter time-scales than the Earth system itself, intensive but time-limited studies (e. g. dedicated one-time exploratory missions and process-oriented ground-based and airborne field studies) can provide sufficient information to reach conclusive results. Based on the criteria laid out above, scientific priority is given to "feedback processes" that have the largest potential for amplifying or damping changes in the global Earth system (and may thus induce large uncertainties in potential responses). The observational parameters most closely associated with response studies are summarized in Table 4.4.

- (1) **What are the effects of clouds and surface hydrologic processes on climate change?** The formation, life cycle and optical properties of cloud systems remains, to this day, the largest source of uncertainty in simulations or predictions of global climate change. Clouds affect climate both directly, through their controlling effect on the planetary radiation balance, and indirectly, through vertical transport and condensation of water vapor that controls upper-tropospheric moisture and its greenhouse effect. Conversely the formation, life cycle and radiative properties of clouds are governed by the relative humidity of surrounding clear air. Thus, the feedback effects involving climate, clouds, and surface water can be significant and must be understood.

Cloud processes involve complex 3-dimensional interactions between fluid dynamical motions, microphysical and optical properties of liquid and ice cloud particles, pre-existing condensation nuclei (aerosols), and the dynamics of the mesoscale weather systems in which they are embedded. These complex interactions generate extremely diverse cloud systems and cloud types, each involving different controlling microphysical and meteorological factors. Understanding these complex phenomena requires observations that simultaneously (1) resolve the 3-dimensional structure of cloud systems, (2) cover a representative sample of all different cloud types and distributions of condensation nuclei and aerosol particles that affect cloud particle distributions, (3) characterize the large-scale weather patterns and/or mesoscale disturbances that generate the clouds, and (4) relate cloud dynamics and optical properties to large-scale climate variables, especially the thermodynamic structure of the troposphere and radiation fluxes at the top of the atmosphere. These observational requirements have only been partially met so far by regional field observation campaigns focused on one or a few cloud types.

The *surface hydrologic processes* that govern continental water budgets and the availability of fresh water resources also are the result of complex physical and biological processes taking place at the land surface. Land surface hydrologic processes control river flow and available water resources, diurnal variations in surface temperature, and the availability of soil moisture that sustains the growth of terrestrial ecosystems. So far, basic hydrologic processes have been examined mainly at the scale of relatively small river basins or catchments. Quantitative understanding of hydrologic processes over large areas, commensurate with the scale of climate phenomena, will require a breakthrough in large-scale observation of hydrologic properties and physical climate drivers. Specific observational requirements to address this problem include (in addition to atmospheric properties, precipitation and

surface radiation fluxes) exploratory measurements of soil moisture, snow accumulation and snowpack, and the transition between frozen and thawed soil conditions.

(2) **How do ecosystems respond to and affect global environmental change and the carbon cycle?**

Terrestrial and marine ecosystems are affected by multiple environmental stresses and disturbances, as well as natural cycles, that can result in changes in primary productivity, continental and oceanic carbon sources and sinks, the biogeochemical cycles of carbon and important nutrients, surface energy balance, and surface hydrological processes. Response processes in ecosystems need to be understood at the level of basic functional and structural changes. Ecosystem functional responses involve changes in physiology and biogeochemical cycling. Ecosystem structural responses involve changes in species composition, biomass density, canopy architecture, and distribution patterns across a landscape or within the ocean. Ecosystem responses, in turn, can provide feedback to the climate system and atmospheric chemistry through alterations in the fluxes of water, energy, and trace gases to the atmosphere.

In order to estimate carbon dioxide sources and sinks on the land, ecosystem science needs to quantify the responses of terrestrial ecosystems to disturbance in terms of *biomass changes*, and consequent carbon sequestration or emission. There is no direct method for estimating total biomass by remote measurements, but quantifying above-ground biomass appears feasible, based on experiments performed from the Space Shuttle. A fuller implementation of this concept is under development, and future exploratory projects have been proposed, to address biomass accumulation in ecosystems responding to disturbance.

The global ocean carbon cycle is dominated by the solubility pump (changes in the ability of the ocean take up CO₂), which is driven by changes in ocean temperature and circulation. The biological pump is another critical component of the ocean carbon cycle and involves sinking, diffusion, and active transport of biologically-produced carbon compounds. The CO₂ balance of the atmosphere and ocean can be affected by the biological pump through the effects of changes in limiting nutrient supplies. The observational requirements are long-term observations of the ocean circulation and temperature, ocean productivity, and estimates of the major phytoplankton groups in the upper ocean. Coastal ecosystems are highly productive and extremely variable, and human impacts on the ocean are greatest in coastal regions, as are the impacts of climate variability and sea-level rise. Thus, priority is given to quantifying variability in *coastal primary productivity*. Coastal biological processes are constrained by geography and can be characterized by observations that resolve weather-induced changes (e. g. transient sediment transport events) and tidal fluxes. The principal observational requirement is quasi-continuous observation of ocean color in selected coastal regions, with appropriate spatial, temporal and spectral resolution.

Quantifying regional *carbon sources and sinks* for both the ocean and land can be approached through the inversion of precise measurements of spatial and temporal variations in the total column amount of CO₂ in the atmosphere. The method, founded on the use of inverse atmospheric transport models for analyzing atmospheric concentration data, has the potential for independent direct determination of global CO₂ fluxes. Possible space-based measurement methods are at an early conceptual stage. Information on vertical variations in atmospheric CO₂ may be needed as well to help understand the column measurements. The extent to which such measurements are needed is a research question, however.

(3) **How can climate variations induce changes in the global ocean circulation?** In addition to the main currents and vortices visible at the surface, the ocean also sustains a slow but massive overturning circulation, which involves the formation of "deep water" that sinks to intermediate or bottom depths, and a general upwelling motion that maintains the sharp separation of superficial waters from the deep ocean. This overturning circulation has profound implications on the long-term storage of excess heat and chemicals in the ocean's depths; the recycling of nutrients; marine productivity and the carbon cycle; and the long-distance transport of heat from one ocean basin to the

other. A potential transition from the current circulation regime of the Atlantic ocean to a regime where deep water formation is blocked would have a major climatic impact on the North Atlantic region. There is strong paleoclimatic evidence that such transitions did occur in the past, notably during the recovery from the last glacial episode.

Deep water formation is quite sensitive to a freshening of surface waters, either through the import and subsequent melting of sea ice, or climate-induced changes in the fresh water balance of the ocean at tropical and mid-latitudes. Since atmospheric temperature at high latitude always falls below the freezing temperature of sea water, the fate of superficial waters and their ability to sink into the deep ocean depends upon their pre-existing salinity (salinity and temperature are the two parameters that determine water density). Thus, the principal observational requirements for investigating the potential for a transition in ocean circulation regime are (exploratory) measurements of *sea surface salinity* and *sea-ice* (formation and life cycle).

(4) How do stratospheric trace constituents respond to climate change and chemical agents?

Climate change associated with increasing concentrations of trace gases will affect the distribution of ozone in the stratosphere, and vice versa. The connection between atmospheric temperatures and stratospheric composition is equally well established. A striking example is the enormous interannual variations in wintertime ozone concentration over the Arctic, highly correlated with changes in stratospheric circulation and temperature driven by the troposphere. Long, cold winters, such as occurred in 1996-1997, enhance ozone destruction and make Arctic conditions more similar to those in the Antarctic that enable the annual springtime depletion of ozone.

It has been suggested that climate change will affect the way in which the troposphere influences the stratosphere, and would thus indirectly affect stratospheric ozone. The impact would be particularly strong if the wintertime polar vortex became more stable. Similarly, chemical reactions that occur on the surface of stratospheric aerosol and/or cloud particles are temperature dependent; even a small decrease in temperature could cause a significant increase in the rates of these reactions. Changes in stratospheric water vapor, associated with changes in fluxes through the tropopause, could also enhance the formation of aerosol and cloud particles that facilitate ozone destruction. Furthermore, since ozone absorption of solar UV radiation causes stratospheric heating, a decrease in ozone amount would result in further cooling, and further accelerate ozone losses. There is already strong evidence of cooling in the lower stratosphere, which constitutes one of the largest temperature signals measured in the atmosphere over the past 20 years.

Improving our understanding of this highly interactive system calls for detailed investigation of the relationship between the distributions of ozone, water vapor, aerosols, temperature, and relevant trace constituents, notably chlorine and bromine compounds and nitrogen oxides. In view of the high spatial variability of these phenomena, good horizontal and vertical resolution will be needed, especially in the vicinity of the tropopause (upper troposphere and lower stratosphere).

(5) How is global sea level affected by climate change? There are two major processes by which global climate change may lead to a rise in sea level. First, thermal expansion of liquid water may raise sea surface levels to the extent that the oceans continue to warm in the future. Second, melting of the polar ice sheets has the potential to lead to an increase in the volume of liquid water on Earth. In order to understand the possible impact of the latter process, the way in which ice sheets respond to changes in climate must be understood, which requires more detailed knowledge of the internal workings of polar ice sheets.

The traditional concept of continental ice sheets as a sluggish component of the Earth system, changing with literally "glacial" slowness, is being superseded by the realization that parts of the ice

mass are actually capable of changing substantially over periods of a few years or decades. The dramatic calving of vast tabular icebergs from relatively unstable ice shelves surrounding the Antarctic Peninsula is a portent of such changes. The first high-resolution radar survey of the Antarctic ice sheet discovered massive ice-streams, huge rivers of ice reaching far inland and leading to the ice sheet margin. Assessing the potential for relatively fast ice flows that could discharge vast volumes of ice in a matter of decades instead of centuries is an important problem, considering the potential impacts of an accelerated rate of sea level rise. The observational requirement is mapping the *velocity fields* of the two great ice sheets of Greenland and Antarctica in order to identify their dynamic regions and estimate the mass fluxes of major ice streams. The relevant (synthetic-aperture radar) data might be obtained commercially, or from dedicated national or international scientific measurement missions.

- (6) **What are the effects of regional pollution on the global atmosphere, and the effects of global chemical and climate changes on regional air quality?** The continued growth of the world's population and increasing industrial development imply increasing human impacts on the global atmosphere. As fossil fuel combustion increases, emissions of trace gases other than carbon dioxide will also rise, notably nitrogen oxides, carbon monoxide, hydrocarbons, and other precursors of ozone production, as well as aerosol particles and their precursors.

Satellite observations provide evidence of the large-scale effects of such emissions on the troposphere. The highest tropospheric ozone concentrations observed in this way were found in summertime over mid-latitude regions of the northern hemisphere, and also over the tropics in regions affected by biomass burning. Aircraft observations have demonstrated that plumes of pollution produced by fires can be transported thousands of kilometers to otherwise pristine regions of the atmosphere (e. g., over the Pacific Ocean). Surface level trace gas measurements made on the west coast of the United States show enhanced levels of ozone precursors during periods of rapid and direct transport of air from East Asia.

There are currently few global observations of tropospheric ozone, key trace gases or aerosol particles, and none providing nearly the required vertical resolution. Global measurements of key tropospheric constituents at high vertical and temporal resolution are the condition for progress in understanding the large-scale transport, physical removal and chemical transformation of chemical effluents in the troposphere. In the interim period, some of the high vertical resolution measurements needed can be obtained from balloon and airborne observations (albeit with very limited spatial and/or temporal coverage), as well as the lower resolution space-based measurements that are becoming available for the first time. The capability to observe, from geostationary or Lagrange point platforms, the diurnal evolution of ozone and/or aerosol amounts in polluted regions may also provide significant insight into the balance between processes which result in chemical transformation, physical removal, and physical transport of pollutants.

Table 4.4 Special Observational Requirements for Response and Feedback Process Studies

Parameter / Question	Implementation Detail	In Situ Measurements	Technical Readiness	Operational Potential thru 2010	Partnership Potential
Cloud System Structure (R1)	Multispectral visible and IR radiometry	Radiosondes, lidar (NASA, NOAA, FAA)	Excellent	NOAA & NPOESS requirement	EUMETSAT and Japan's ADEOS/GLI
Cloud Particle Properties and Distribution (R1)	Active sensor to resolve three-dimensional structure	none	Demonstration of cloud radar and lidar pending	Not currently an operational requirement	Domestic and international
Earth radiation Budget (R1)	Broadband radiometry	none	Excellent	Planned on NPOESS	Possible
Soil Moisture (R1)	Spatial resolution and ability to penetrate vegetation required	neutron probes, lysimeters (USDA, USGS, FAO)	Approaching readiness (done from aircraft)	Highly desired; subject to operational viability	Likely with European Space Agency
Snow Cover & Accumulation (R1)	Need to assess snow depth or water equivalent quantitatively	Snow transects (NOAA/NWS)	Awaiting demonstration	NPOESS requirement for snow cover	Possible
Freeze-Thaw Transition (R1)	Need to assess in all sky and surface conditions	Not a routine measurement	Awaiting demonstration	Desired	Possible
Biomass (R2)	Based on resolving canopy vertical structure; requires active lidar sensor	Crop/Timber yield (USDA, DOI), carbon database (DOE)	Demonstration pending (VCL)	Not currently an operational requirement	Possible
Marine Productivity in Coastal regions (R2)	High spatial and temporal resolutions needed	NASA-SIMBIOS; Coastal bio-optics (NOAA, EPA)	Excellent	Possible NPOESS derived product	Active currently
Carbon Sources and Sinks (R2)	CO ₂ , CH ₄ column mapping is most promising approach;	Flask network (NOAA), Ameriflux/Flux Net (DOE, USDA, NASA)	Experimental technique, needs further develop.	Not currently an operational requirement	Possible
Sea Surface Salinity (R3)	Very high radiometric precision needed for passive μ wave observation	Ships and moored/drifted buoys (NOAA/NSF)	Approaching readiness (done from aircraft)	Unfulfilled NPOESS requirement	Likely with European Space Agency
Sea Ice Thickness (R3)	Significance of ice freeboard observations remains to be established	Moored buoys (ONR)	High spatial resolution radar; develop. needed	Desirable	Possible with domestic / international partners
Atmospheric Properties in Tropopause Region (R4)	Need ozone, water vapor, temperature at high vertical resolution	Sondes (WWW, NOAA)	Limb viewing sensors not yet demonstrated	Not currently an operational requirement	Interest exists
Polar ice sheet velocity (R5)	Synthetic aperture radar interferometry; high latitude coverage (polar orbit) needed	GPS (NASA, NSF)	Demonstrated	Desireable	Possible
Tropospheric Ozone and Precursors (R6)	Need excellent vertical resolution through entire troposphere, implies active lidar sensor	Airborne in situ for DC-8, R-2, WB-57	Experimental technique, needs further develop.	Not currently an operational requirement	Interest exists

4.4 Consequences of Global Changes

The consequences for human civilization are the root of societal interest in the prospects for global environmental change. Changes in the Earth's land cover and land use are pervasive and increasingly rapid; few landscapes are unaffected and the coastal ocean is increasingly disturbed. Changes in global mean climate quantities (e. g. surface temperature) elicit broad interest because of the surmise that relatively small variations in atmospheric composition and greenhouse effect, atmospheric circulation and ocean temperature, land cover or land use, could result in serious disruptions of the natural environment. Concern about human consequences is not limited to considerations of the future. Currently occurring changes can affect properties of direct interest to human societies: the availability and quality of water, the quality of air, the health and diversity of ecosystems, the ability for diseases to spread, and the sustainability of agricultural production.

Consequences can take many forms, from impacts on air quality to changes in solar UV radiation, loss of biodiversity, or degradation of ecosystem productivity. These impacts are of considerable societal significance and warrant dedicated local investigations that are beyond the scope of the NASA Earth science research program. Assessing the existing or potential impacts of environmental change is a widely shared responsibility of several partner agencies of the USGCRP; the ESE's participation to this effort involves, in particular, the deployment of unique remote sensing assets and is handled principally through the ACE program. Three research areas involving large-scale or even global impacts are given particular attention in the ESE research program.

The observational parameters most relevant for consequence studies are summarized in Table 4.5.

(1) **How are variations in local weather, precipitation and water resources related to**

global climate variation? The striking manifestations of "El Niño weather" in many regions of the world, including western and southeastern US, are a clear example of the climate-weather connection. Much remains to be learned, however, about the relationship between observed trends or anomalies in global-mean atmospheric state and associated changes in the path, frequency and intensity of weather systems. The information needed to document changes in the global atmospheric circulation and climate was considered in 4.1(1) and 4.3(1) above. The new challenge is that of relating the large-scale atmospheric circulation to the life cycle of mesoscale storms (e. g. hurricanes) and other severe weather systems (e. g. tornado-generating rainstorms), and then understanding how that relationship might change in a future climate. Another challenge is that of deriving quantitative precipitation predictions from weather forecasting models. Both topics are actually central objectives of the US Weather Research Program. The special observation requirements to address these objectives are principally *global precipitation* and *ocean surface wind*, the latter providing a direct measure of storm tracks, strength, and life cycle over the expanses of the ocean. Another potential source of observational data on the life cycle of mesoscale storms (principally over land) is the measurement of the 3-dimensional structure of atmospheric *temperature, moisture and wind* around storm cells. Other developmental observations (e. g., imaging lightning strokes from a geostationary platform) may also reveal important new information regarding thunderstorms, severe weather and rainfall.

The other major impacts of global climate change are regional hydrologic anomalies, floods and droughts, as well as long-term variations in the availability of water resources, changes in the distribution and/or seasonal variation of wetland area, and the volume of inland water bodies (e.g. the Caspian sea). The principal challenge in this domain is also the quantitative prediction of

precipitation. In addition, exploratory observations of soil moisture, snow accumulation, and freeze/thaw transitions (see the first question in the response section) will provide critical process-level information needed for predicting the hydrologic consequences of regional climate anomalies. Basic hydrologic data such as *river stage height* and/or *discharge rate* are often unavailable for scientific studies, even for some of the world largest river basins. As the competition for water resources increases, it is even less likely that such basic hydrologic data will be freely exchanged in the future. This information is an essential observational requirement for the study of regional hydrologic impacts. For measurements of these quantities, use of in situ measurements to help relate measurements of stage height to discharge rate are of particular importance.

- (2) **What are the consequences of land cover and land use change for the sustainability of ecosystems and economic productivity?** To understand the consequences of land cover and land use change for sustainability of ecological goods and services, both the biophysical and the human factors that both drive and constrain land cover and land use changes must be addressed. Natural and human-induced disturbances such as fire, insect infestations, and logging may change large areas of the Earth's surface, but more subtle changes that result in habitat degradation and fragmentation (e. g., forest clearing and/or burning, land use change associated with urbanization) or the introduction of non-native species can lead to diminished ecosystem functionality, redistribution of species within an area, and/or loss of biodiversity. The impacts on agriculture, forestry, and water resources; biodiversity; carbon storage or release; and the geographic distribution and activities of human populations need to be quantified. Satellite observations, especially high-resolution multispectral image data acquired to estimate primary productivity, document land cover patterns, or assess change in ecosystem properties (see 4.2), also can contribute to assessing such consequences and identifying those regions most susceptible to changes in species distributions. The verification of these changes and the identification of the impacted species is best carried out through *in situ* studies that will typically be carried out by agencies other than NASA.
- (3) **What are the consequences of climate and sea level changes and increased human activities on coastal regions?** Coastal regions, including beaches, low lying lands near oceans, estuaries, and river deltas, are of particular importance to human societies, especially since the population that lives close to the ocean is fast increasing worldwide. Such regions are highly susceptible to the effects of sea level rise (including wetlands loss), disturbance by human activities, and land cover changes in adjacent watersheds, as well as a potential increase in the frequency and amplitude of storm surges associated with the landfall of large storms. Surface erosion due to wind and wave conditions, wind damage, flooding, sediment deposition and chemical pollution (both direct and through runoff from agricultural and urban regions), and hazardous biological phenomena (e. g. algal blooms) are the principal stresses and disturbances observed in coastal regions. Conversely, coastal wetlands in the tropics appear to be large natural sources of ozone-destroying halogenated chemicals. The challenge is characterizing these changes over a long enough period to understand how coastal regions respond to simultaneous changes to these multiple stress factors, and how the forcing factors and response mechanisms might change in a changing climate. The principal observational requirement, in addition to meteorological information and sea-level data, is for repeated multispectral observation (which can provide information on the distribution and properties of biological material) of coastal regions at the highest practicable spatial and temporal resolution.

Table 4.5 Special Observational Requirements for Studying the Consequences of Global Change

Parameter / Question	Implementation Details	In Situ Measurements	Technical Readiness	Operational Potential thru 2010	Partnership Potential
Global Precipitation (C1)	Requires 6-8 satellite constellation for good time resolution	raingauges, weather radar (NOAA, WWW)	Demonstrated via TRMM and passive μ wave imagers	Yes; only passive μ wave currently planned	Excellent – several needed
Ocean Surface Winds (C1)	Active μ wave technique	ships, buoys (NOAA, WWW)	Demonstrated by NSCAT and SeaWinds	Yes	Seawinds cooperation with Japan; EUMETSAT
	Passive μ wave radiometry / polarimetry to be demonstrated	N/A	Windsat/Coriolis demonstration funded by DOD, USN, NPOESS	NPOESS requirement may be fulfilled	Possible
Meteorological Properties Around Storms (C1)	Requires vertical profiling from a geostationary platform	Radiosondes (NOAA, WWW)	Demonstration planned with GIFTS	Yes	Possible
Lightning Rate (C1)	Requires geostationary implementation for temporal resolution	Sferics (NOAA)	Demonstrated by OTD and LIS	Yes	Possible
River Stage Height/ Discharge Rate (C1)	Requires high precision, vertical resolution, and frequent sampling	River gauges (USGS)	Capability demonstrated by Topex/Poseidon	Not currently an operational requirement	Not known
Primary Productivity (C2)	Global 1 km or better resolution needed	NASA-SIMBIOS, GOOS, GTOS, crop, forest inventories (USDA, FAO), LTER (NSF)	Excellent	NPOESS requirement	EUMETSAT coordination
Land Cover / Land Use Change (C2)	High spatial resolution required	Land cover maps (USGS), veg. Inventories (DOI, USDA)	Excellent, need to reduce cost	Not currently	Commercial data sets
Coastal Region Properties and Productivity (C3)	Multispectral radiometry at high spatial and temporal resolution from GEO	Coastal observations (NOAA, EPA)	Excellent	Not currently	Possible

4.5 Global Change Prediction or Assessments

How well can we predict the changes to the Earth system that will take place in the future? Beyond the broadly shared interest in understanding the causes (why?) and the mechanisms (how?) of environmental changes, the capability to deliver specific and verifiable predictions of future environmental events or trends would be of considerably higher practical value. In particular, it is important that individual, governmental, or business decisions which depend on consideration of the future environment be made on the basis of the best possible scientific information. Such decisions can have important consequences at all levels of society. When future forcings are uncertain, multiple forecasts must be carried out in order to define the probable range of responses.

Most environmental change issues of importance to decision makers are of local or regional scope, rather than global. While the focus of the ESE research program is on scientific questions concerning the global environment and large-scale Earth system phenomena, it is often the case that knowledge acquired about global changes and trends can be translated into regionally specific but only statistically valid predictions or assessments. Providing prediction services is the mission of responsible operational agencies, not NASA. On the other hand, it is incumbent upon NASA, like other research and development agencies, to assist in the improvement of such prediction services of great societal importance, within the scope of its special capabilities. These capabilities include various global observing assets and predictive models, as well as the capability to combine observations and models. It is apparent that successful prediction is the ultimate step in the progression from basic global observations of Earth system variations and trends (both natural and human-induced), to understanding the internal processes and responses, to assessing the consequences. The ESE research program is especially relevant to five types of prediction or assessment of future changes.

The new observational parameters most clearly associated with improved capability for prediction are summarized in Table 4.6. Although all the variables cited in the previous tables may be thought of as potentially contributing to this improvement, this table lists only those parameters that are considered to have the greatest potential impact on prediction, focusing on the short-term.

- (1) **How can weather forecast duration and reliability be improved by new space-based observations, data assimilation, and modeling?** Accurate forecasting of weather is of considerable significance for the protection of lives and property. Improving the accuracy of short-term predictions and increasing the period of validity of long-range forecasts has great practical interest and is a great scientific challenge. While weather prediction is the primary responsibility of operational agencies, such as NOAA in the US, scientific advances made in developing more accurate climate and/or Earth system models, as well as more effective methods for ingesting new types of observations, are directly applicable to the improvement of operational forecasting systems. Experience showed that synergy between operational weather forecasting practice and the development of new observation systems or products is an effective engine of progress in both domains. The principal thrusts of ESE's cooperation with operational weather services are (1) participation in the development of precursor operational instruments for application to various operational environmental satellite systems, (2) development of new data products originating from space-based observing systems, and (3) collaboration in the development and experimentation of improved atmospheric circulation models and data assimilation schemes.

The ESE participates in the development and flight demonstration of future operational NPOESS and GOES instruments, and the development of innovative remote sensing systems that may find operational applications in the future (e. g. tropospheric wind sounder). The ESE also supports

cooperative modeling research and development efforts with NOAA's National Centers for Environmental Prediction, as well as the National Center for Atmospheric Research.

- (2) **How well can transient climate variations be understood and predicted?** Short-range climate forecasts (for periods from a season to a year) are of considerable value to businesses, resource management agencies, and farmers. Improved atmospheric circulation models and coupled ocean-atmosphere models have demonstrated predictability in climate variations up to several months in advance for some regions of the world. Numerical simulations have also demonstrated the sensitivity of such predictions to a number of land surface and ocean circulation parameters. An essential condition for capitalizing on these scientific advances is access to the relevant geophysical information and the ability to ingest this information through more effective data assimilation methods. The information most useful for this application includes, in order of increasing persistence or "memory": *ocean surface winds; continental soil moisture; sea surface temperature; ocean sub-surface temperature and currents* (alternatively, *ocean surface topography*). Initial values of tropical ocean parameters are principally useful for ENSO prediction, while continent-scale soil moisture data (not yet available with the required coverage and accuracy) significantly influence numerical predictions of summertime precipitation over the interior of continents. Recent progress in seasonal prediction has come from realistic representation of mesoscale weather systems in coupled global atmosphere-ocean models (to be expected since the principal manifestations of transient climate anomalies are changes in storm track, frequency, and strength). The ESE's research program contributes to progress in all aspects of this problem, from improvements of models and data assimilation methods to advances in global observation.
- (3) **How well can long-term climatic trends be assessed or predicted?** The long-term prediction of potential changes in global climate is the most daunting challenge of all, because such predictions depend critically on accurate representation of all relevant "feedback processes" in the atmosphere, ocean, soil and ice, and the biosphere, as well as realistic scenarios about future changes in primary forcing factors. Among the most critical problems are understanding the atmospheric processes that vertically redistribute energy, water and other constituents in the atmosphere; the relationship between cloud radiative properties and the underlying meteorological conditions; the partitioning of rain and snow among evaporation, storage and runoff; the effects of changes in land surface and land use on the latter; the exchanges of energy, fresh water, and trace constituents between the atmosphere and the ocean; the formation and evolution of sea ice; the influence of physical climate on biogeochemical cycles; and the trace gas composition of the atmosphere and response to changes atmospheric circulation. Building confidence in such predictions requires success in all four preceding steps in the science strategy.

Another piece of information that will eventually be needed for specific predictions of multi-decadal climate changes is an accurate description of the state of the deep ocean circulation globally, a task already undertaken under the international World Ocean Circulation Experiment and follow-on global ocean observing and data assimilation programs. Because of the fundamentally chaotic nature of fluid and climate system dynamics, any long-term prediction effort should be based on not just one, but a number of alternative model runs in order to quantify and minimize the range of natural variability. Such "ensemble forecasts" pose major computational demands that cannot be fulfilled without significant increase in computing capabilities and developments in computational software and algorithms used in climate models.

- (4) **How well can future atmospheric chemical impacts on ozone and climate be assessed?** Prediction of the evolution of atmospheric trace constituent composition is intimately linked to that of the meteorological conditions under which chemical and transport processes occur. The chemical

constituent of greatest interest is ozone, which both protects the Earth from biologically damaging solar ultraviolet radiation, and is an active chemical agent pollutant that affects both plant and animal life. Ozone responds (for both production and destruction) to the concentration of many precursor species coming from both natural and anthropogenic sources. Accurate modeling of atmospheric composition requires knowing or forecasting the future evolution of these chemical forcings as well as relevant changes in climatic conditions. In the case of sufficiently large changes in atmospheric composition, interactions with resulting changes in atmospheric circulation and physical properties cannot be ignored (the chemistry of the polar stratosphere is an important case in point). Processes of particular importance for model assessments of potential atmospheric chemical composition impacts include the transport of material between the troposphere and stratosphere; the formation of aerosols and cloud particles and of their interactions with gas phase species; the natural and human-induced variability in biological sources and sinks; and the balance between chemical removal and long-range tropospheric transport.

(5) How well can cycling of carbon through the Earth system be modeled, and how reliable are predicted future atmospheric concentrations of carbon dioxide and methane by these models?

To predict future climate changes and global productivity patterns, it will be necessary to develop realistic projections of the atmospheric concentrations of carbon-containing gases such as carbon dioxide and methane. These projections require understanding the interactions between the biosphere and the physical environment (especially temperature, precipitation, and carbon dioxide and methane concentrations for the terrestrial biosphere; ocean circulation for the marine biosphere; and changes in nutrients for both), as well as the basic relationships between the physical environment, human management activities (e. g. land use, fishing), and biological activity. A combination of global observation of the biosphere (including vegetation cover, above-ground biomass, and the distribution of chlorophyll in the ocean) and global biospheric models will be needed.

In order to predict how carbon cycling might change in the future, observations and representations of carbon cycling processes must be incorporated into terrestrial and oceanic ecological and biogeochemical models, as well as land cover change models. In addition, new and improved carbon cycle models will be necessary to calculate emissions for different landscapes, regions, oceans and the entire Earth system. Inverse modeling may be used to test our understanding of trace gas emissions in the light of observed atmospheric distributions and knowledge of carbon cycling processes. Such models will be important to assess our ability to simulate the past evolution of trace-gas concentrations and build up confidence in prediction capabilities for the future. The ESE will rely largely on information developed by NASA's partners in the USGCRP about future carbon dioxide emissions from fossil fuel combustion and methane emissions (e. g. from landfills, cattle, rice paddies, and natural gas production).

Table 4.6 Special Observational Requirements for Prediction and Assessments

Parameter / Question	Implementation Detail	In Situ Measurement	Technical Readiness	Operational Potential thru 2010	Partnership Potential
Tropospheric Winds (P1)	Active Doppler lidar remote sensing	rawinsondes (NOAA, WWW)	Technical developments, demonstration needed	Very high	Commercial data purchase possible
Ocean Surface Winds (P1)	Active μ wave technique	ships, buoys (NOAA, WWW)	Demonstrated by NSCAT & SeaWinds	Yes	Seawinds cooperation with Japan; EUMETSAT data acquis.
	Passive μ wave radiometry/polarimetry	N/A	Windsat/Coriolis demonstration funded by DOD, USN, NPOESS	NPOESS requirement may be fulfilled	Possible
Global Precipitation (P1)	Requires 6-8 satellite constellation for Good time resolution	Rain gauges, weather radar (NOAA, WWW)	Demonstrated via TRMM and passive μ wave imagers	TBD; only passive μ wave currently planned	Excellent – several needed
Freeze-Thaw Transition (P1)	Need to assess in all cloud and vegetation conditions	Not a routine measurement	Awaiting demonstration	Desired; subject to operational viability	Possible
Lightning Rate (P1)	Requires geostationary implementation for temporal resolution	Sferics	Demonstrated by OTD and LIS	Could be implemented on future GOES	Possible
Soil Moisture (P1, P2)	Spatial resolution and ability to penetrate vegetation are crucial	neutron probes, lysimeters (USDA, USGS, FAO)	Approaching readiness (done from aircraft)	Highly desired, subject to operat. viability	Possible
Sea Surface Temperature (P2)	Both IR and μ wave observations needed for all-weather measurement	ships, buoys (NOAA, WWW)	Excellent	NPOESS requirement	EUMETSAT coordination
Ocean Surface Topography (P2)	Prefer non-polar orbit to avoid tidal aliasing	Tide gauges; Global Geodetic Network for reference frame	Demonstrated ; development needed for denser coverage	Included on one NPOESS sat. but polar orbit is problematic	Continuation of past partnership likely
Deep Ocean Circulation (P3)	Requires <i>in situ</i> oceanographic observations	Ships and ARGO floats (NOAA, NSF)	WOCE, GODAE research projects provide initial data base	Operational Global Ocean Observing System is being envisaged	Multi-agency, international cooperation is anticipated
Total Column Ozone (P4)	High long-term accuracy needed for trend studies	Dobson, Brewer, FTIR, UV/VIS (NASA, NOAA)	Excellent	NPOESS requirement	EUMETSAT coordination
Trends in Carbon sources and sinks (P5)	CO ₂ and CH ₄ column mapping is most promising approach	Flask network (NOAA), Ameriflux/FluxNet (DOE, USDA, NASA)	Experimental technique; needs further development	Not currently	Possible
Land Cover/Land use Change (P5)	High spatial resolution required	Land cover maps (USGS), Veg. Inventories (DOI, USDA)	Excellent, need to reduce cost	Not currently; working with USGS	Commercial data purchase likely

5. INTRODUCTION TO NASA'S EARTH SCIENCE RESEARCH THEMES

The twenty-three research questions formulated in the previous section indicate the complexity of the global Earth environment, the multiplicity of interactions between component processes, and cross-disciplinary connections among them. In addressing these complex problems, the ESE plan for the implementation of its research programs builds on the strength of the existing Earth science disciplines, generally focused on individual components of the Earth system, which provide a common language and the background knowledge for articulating focused science questions and suggesting productive research methodologies. Thus the organization used in the following topical chapters has a strong, but not exclusive, heritage in individual Earth system disciplines, and defines research themes that each address the research questions relevant to a particular disciplinary domain. The plan identifies four environmental research themes which address four among the six topical research areas¹ of the USGCRP, and the three cross-cutting themes² identified by the *Research Pathways* report (NRC, 1999a). The fifth research theme, focused on the study of the Earth's interior (not part of the USGCRP) is founded on a long tradition of scientific excellence acquired by NASA since the beginning of space exploration, and has very significant applications in global satellite navigation systems, geodesy and natural hazard warning. It is important to recognize that the scientific program being implemented is derived directly from the questions enumerated in the previous section.

Although the organization used in the topical chapters reflects principal components of the Earth system, it is critical to emphasize the importance placed within ESE on interdisciplinary science. ESE has a strong research program designed to address interdisciplinary questions, and the Earth system science perspective is being increasingly utilized in the development of the research program.

1. *Biology and Biogeochemistry of Ecosystems and the Global Carbon Cycle*

This component focuses on the study of change in the Earth's terrestrial and marine ecosystems and biogeochemical cycles. It addresses ecosystems as they are affected by human activity, as they change due to their own intrinsic biological dynamics, and as they respond to climatic variations and, in turn, affect climate. Research approaches range from detailed process-level studies, to global-scale observations of productivity and carbon sources and sinks, and to mechanistic modeling of ecosystem dynamics and biogeochemical cycling processes. Emphasis is on characterizing the processes that affect the Earth's capacity for biological productivity, documenting changes in land cover and land use, understanding the role of the biosphere in Earth system function, and quantifying changes in the global carbon cycle, especially major fluxes and the active land, ocean, and atmospheric reservoirs..

2. *Atmospheric Chemistry, Aerosols and Solar Radiation*

The research theme encompasses the processes responsible for the emission, uptake, transport, and chemical transformation of ozone and precursor molecules associated with its production in the troposphere and its destruction in the stratosphere, as well as the formation, properties, and transport of aerosols in the Earth's troposphere and stratosphere (the direct impact of aerosols on atmospheric radiation transfer and effects on cloud formation and properties are discussed in the subsequent chapter on the global water and energy cycle). Since variations in solar activity have considerable influence on

¹ Biology and Biogeochemistry of Ecosystems, Change in the Climate System on Seasonal-to-Interannual and Decadal-to-Centennial Timescales, Change in the Chemistry of the Atmosphere.

² Global water cycle, global carbon cycle, and the climate prediction, including the role and impacts on humans.

atmospheric composition and chemistry, the monitoring of solar radiation (both total irradiance and spectrally-resolved irradiance) is also included.

3. Global Water and Energy Cycle

The principal research objective is to explore the connection between weather processes and climate change and the fast dynamical/physical processes that govern climate responses and feedbacks. Particularly significant is the transformation of water among its three physical states – vapor, liquid, and ice - in the atmosphere and at the surface of the Earth. The condensation of water in cloud and snow control both the albedo and radiation balance of the planet, and the constant renewal of fresh water resources. The development of weather system, the cloud life cycle and their role in the water and atmospheric energy cycles are approached as a single integrated problem. Another central science objective is exploring the responses of hydrologic regimes to changes in climate (precipitation, evaporation, and surface run-off) and the influence of surface hydrology (soil moisture, snow accumulation and soil freezing) on climate.

4. Oceans and Ice in the Earth System

The research theme is principally focused on the slower processes that affect the distribution of large liquid and solid water masses on the planet, the circulation of the Earth's oceans and the mass balance of glaciers and ice-sheets. The oceans and ice-sheets are driven by atmospheric forces: ocean surface wind, changes in ocean water buoyancy brought about by air-sea fluxes of radiation, heat and fresh water (precipitation minus evaporation), sea-ice formation and melting, and snow accumulation on ice surfaces. or snowfall. The research objective is to understand and model the dynamics of the oceans and ice, on all space- and time-scales that are relevant to the dynamics of the coupled ocean-atmosphere system and sea-level rise. Relatively short period and small-scale phenomena associated with upper ocean and coastal zone variability may also be studied, recognizing that process-level knowledge is necessary for predicting the behavior of coupled climate system, for understanding oceanic biological productivity and biogeochemistry, and for many marine applications.

5. Solid Earth Science

This ESE research theme contributes to knowledge in two broad domains of Earth sciences: inferring from observation the motions of the Earth and Earth's interior, and observing how the Earth surface is being transformed as a means to predict future change. The former aims to provides the fundamental knowledge basis for understanding the Earth dynamics (e. g. the precise shape of Earth and its gravity field) as well as supporting a broad range of modern applications (e. g. space-based navigation systems). The latter aims to establish the conceptual and observational framework for assessing the risks associated with natural hazard, such as earthquakes, volcanic eruptions and landslides. On a more fundamental level, the solid Earth science program contributes to understanding how the forces generated by the dynamism of the Earth's interior have shaped landscapes and driven the chemical differentiation of the planet, including recent processes such as volcanic eruptions.

M. Earth System Modeling

The ultimate challenge of Earth system science is to consolidate the scientific findings in the different disciplines into an integrated representation of the coupled atmosphere, ocean, ice, land and biosphere system. This matter is the topic of the final synthesis chapter on Earth System

Observation and Modeling. The hallmark of the ESE program is the integration of observations with model representations: observational data sets without an explicative model provide little insight in the nature of the underlying mechanisms; models without observation provide no verifiable conclusion. Coupled Earth system models are the tool of choice for predicting future variations and trends in the Earth system, most notably that of the Earth's climate system, but including evolution of its chemical and biological components. Such models also provide tools that can be used to contribute to science-based assessments of potential future changes. Data assimilation systems provide a framework for combining global observations with models in order to provide geophysically consistent data sets as well as optimal initial multi-parameter fields which can be used for the improvement of predictive capability, including the initialization of forecast models used for short- to intermediate-term simulation. While models of individual components are described within the relevant topical research themes above, the chapter focuses on modeling research and data assimilation development aiming to investigate the interaction among these components and predict transient variations and trends in the coupled system, such as climatic oscillations (ENSO, NAO, etc.) and longer-term climate change under various forcing scenarios.

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